Applications of ocean colour

and synergies with other sensors and observing systems

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with contributions by Ian Robinson, Stewart Bernard…

Outline

- What can we measure with ocean colour?
- Examples of ocean colour applications
  - Use of ocean colour in numerical modelling
  - Ocean colour and physical oceanography
  - Fisheries and management of marine living resources
  - Water quality
  - Harmful algal blooms and other hazards
  - Transport of sediment and pollutants
  - Oil spill monitoring
  - Commercial shipping and port operations
  - Military applications

Water properties available from ocean colour

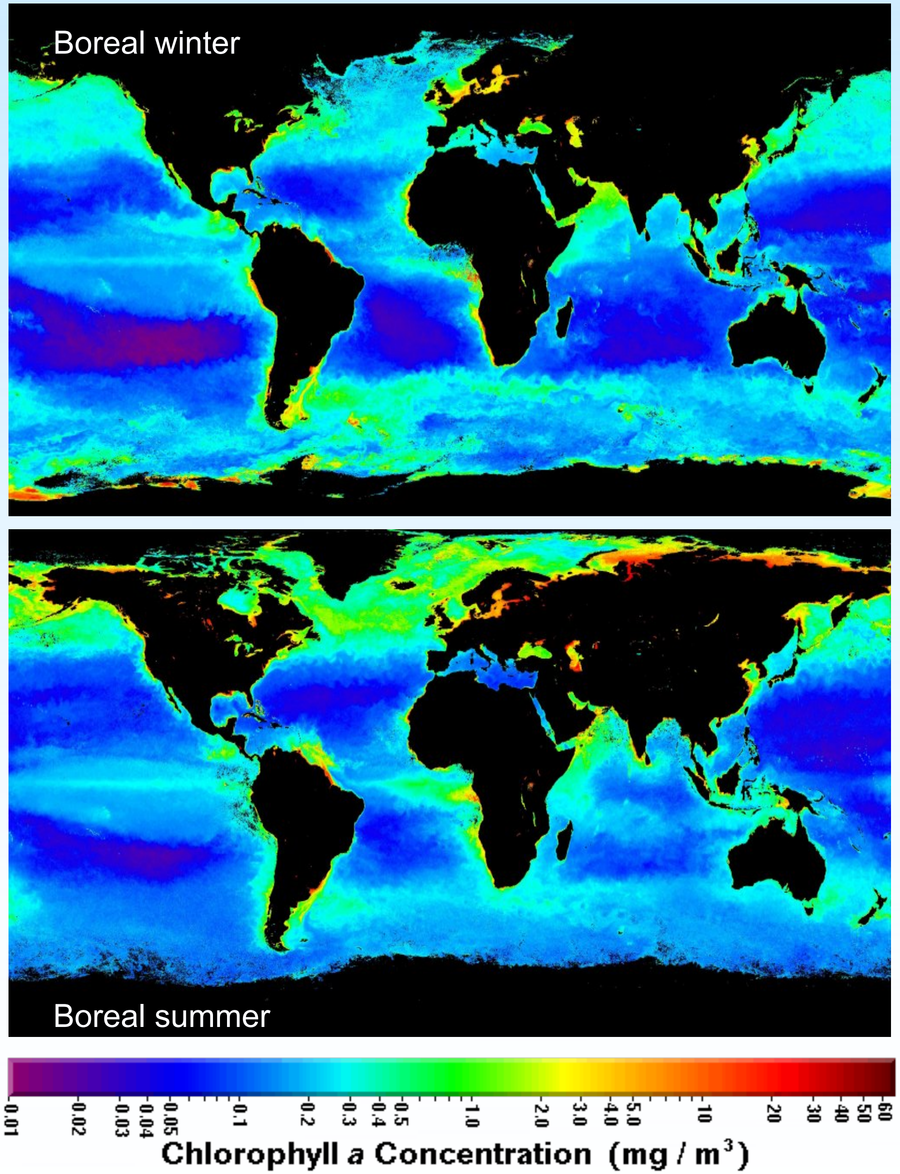
- Chlorophyll concentrations
  - A key parameter in ecosystem function and productivity
  - Water quality indicator
- Diffuse attenuation coefficient (K)
  - An index of water clarity; indicator of water quality
- Suspended sediment and yellow substance (CDOM)
  - Used in studies of sediment transport; indicator of soil erosion
- Spectral reflectances (normalised water-leaving radiances)
  - Basis for in-water optical algorithms to derive other parameters of interest to users
- Photosynthetically active radiation (PAR)
  - How much light is available for photosynthesis

Chlorophyll concentration (1)

- The key geophysical property of sea (and fresh) water monitored with ocean colour radiometry
- An index of phytoplankton biomass
  - Phytoplankton biomass is a basic ecological property
    - Quantifies the ecosystem component primarily responsible for transforming carbon dioxide into organic carbon
    - Basis for the marine (or aquatic) food chain
- Water quality indicator
  - High chlorophyll concentrations are linked to high levels of nutrients (N, P) and can indicate nutrient enrichment arising from human activities
    - Sewage outfalls , fertiliser in land run-off, atmospheric deposition of nitrous oxides (from fossil fuel burning)
- Indicator of ocean dynamics in physical oceanography

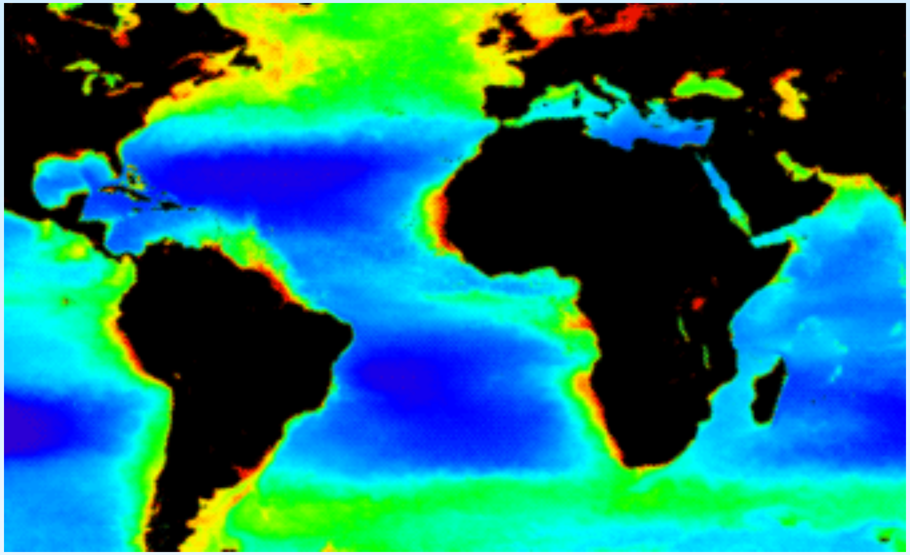
Chlorophyll concentration (2)

The most important parameter from ocean colour satellites

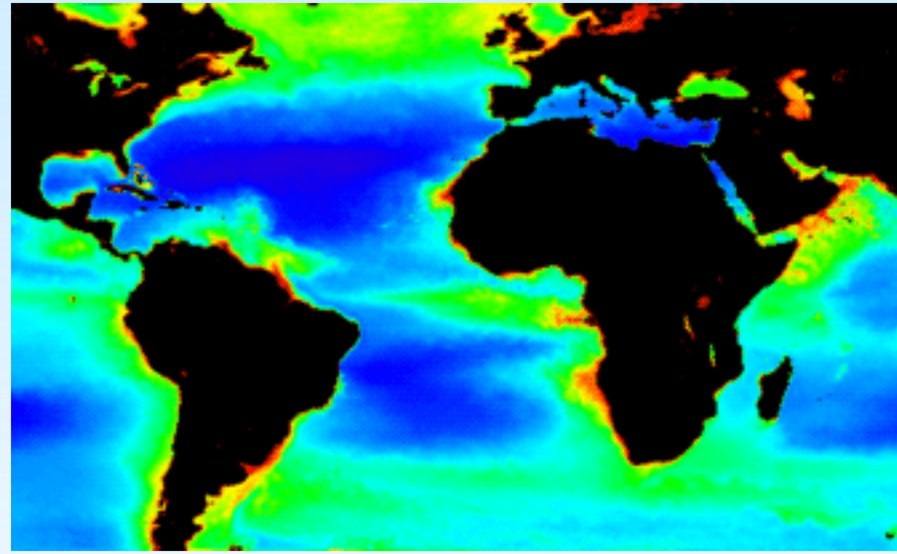


- What is measured?
  - Chlorophyll-*a* and photosynthetic pigments similar to chlorohyll-*a*
  - Based on blue : green R_{rs} ratio
    - Empirical polynomial based on a large in-situ / satellite match-up data set
- Units: mg m^{-3} = μg l^{-1}
- Standard product from:
  - SeaWiFS (1997-2010)
  - MODIS Aqua (2002-present)
  - MERIS (2003 – present)
- Surface concentrations only
- Uncertainty
  - <35% in most areas
  - >35% in Case II water, Antarctic
    - Also elsewhere during very intense plankton blooms (Chl-a > 50 mg m^{-3}

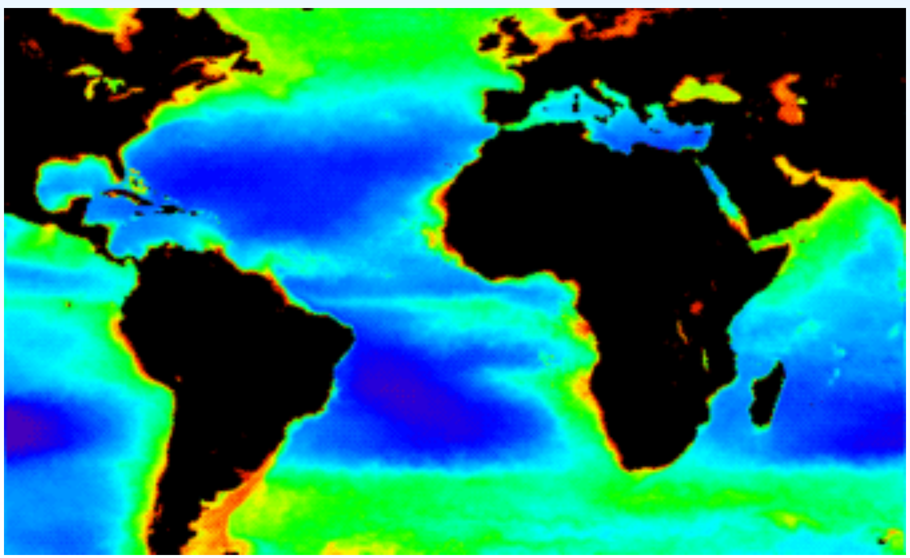
Seasonal chlorophyll climatology



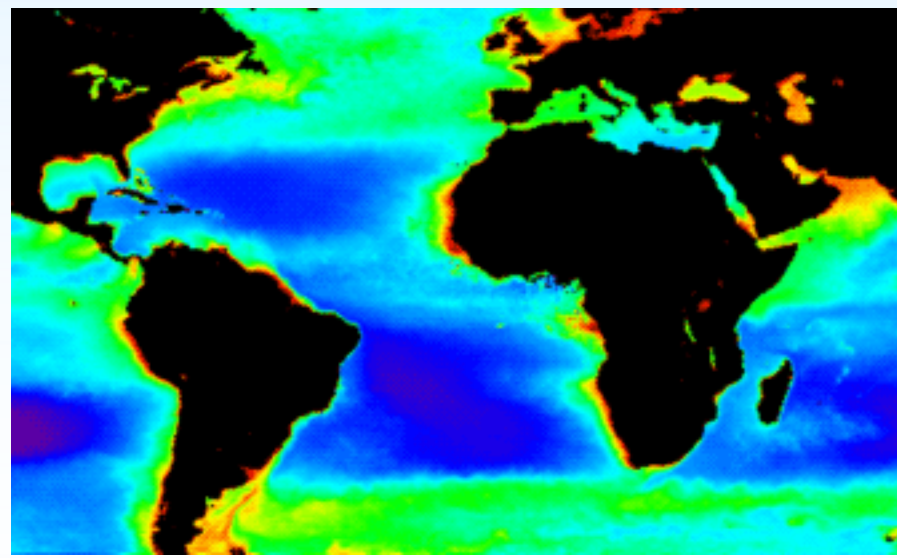
March – May



June - August



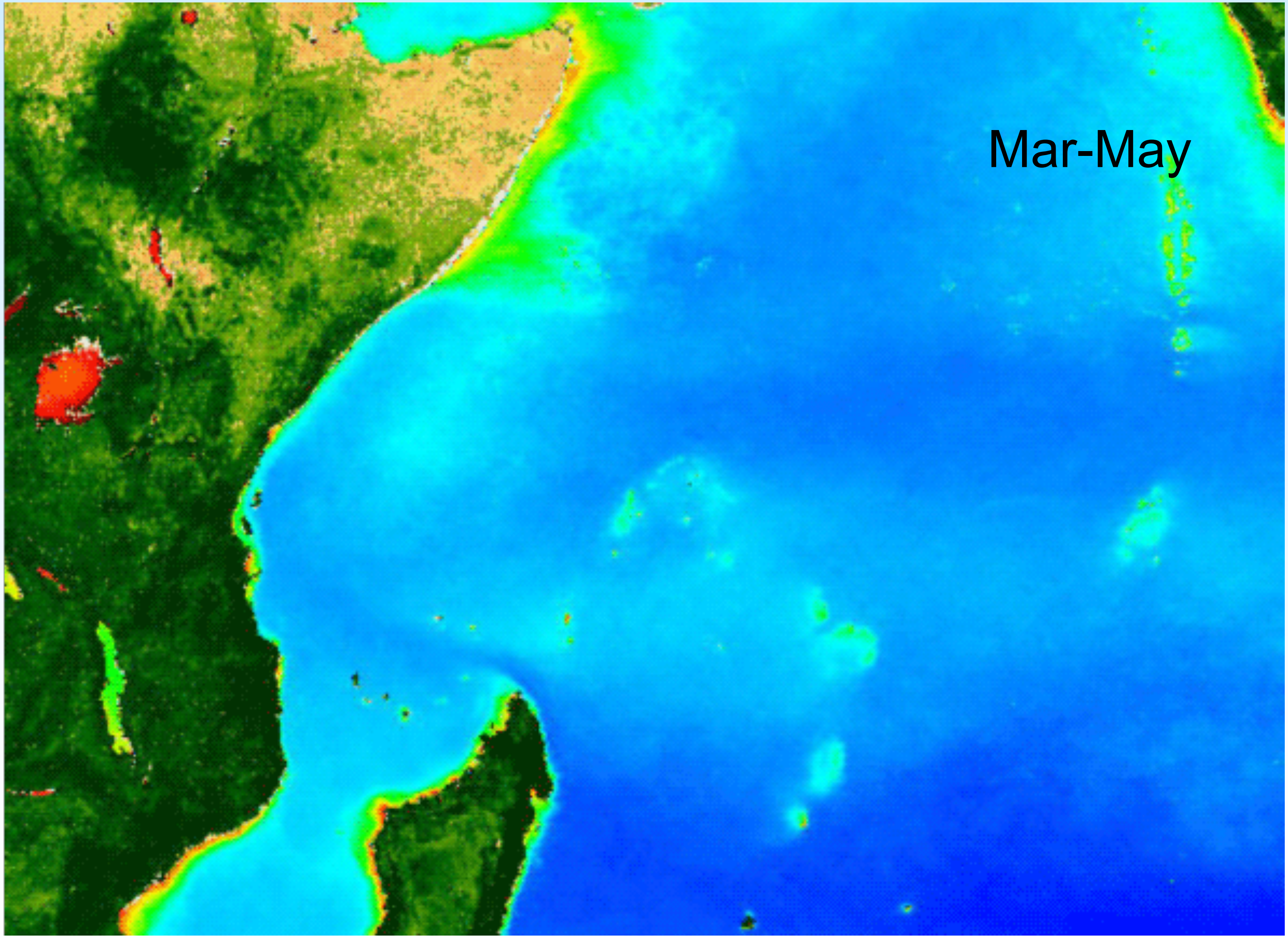
September – November



December - February

NASA MODIS-Aqua

Seasonal chlorophyll variability in the NW Indian Ocean



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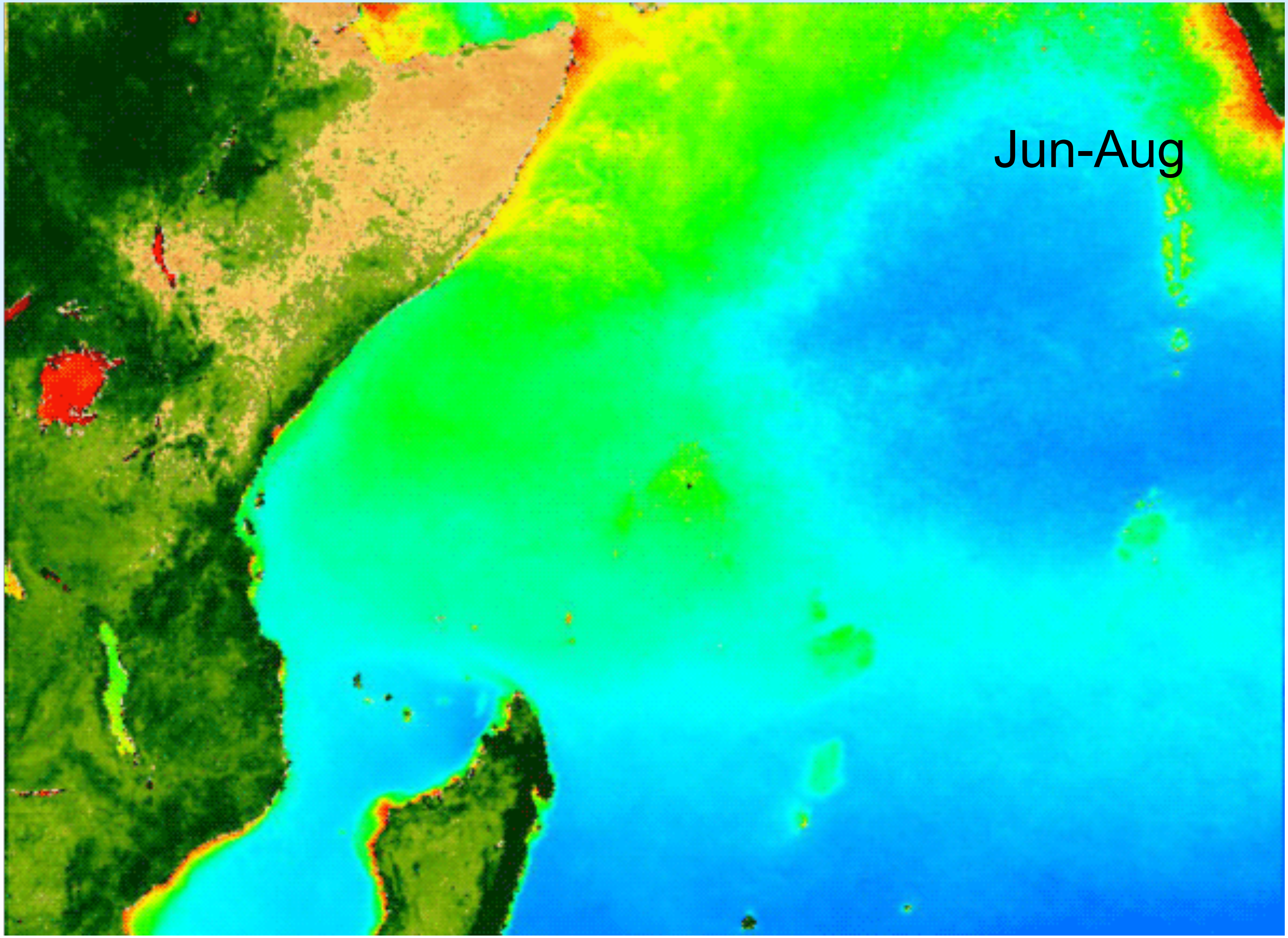

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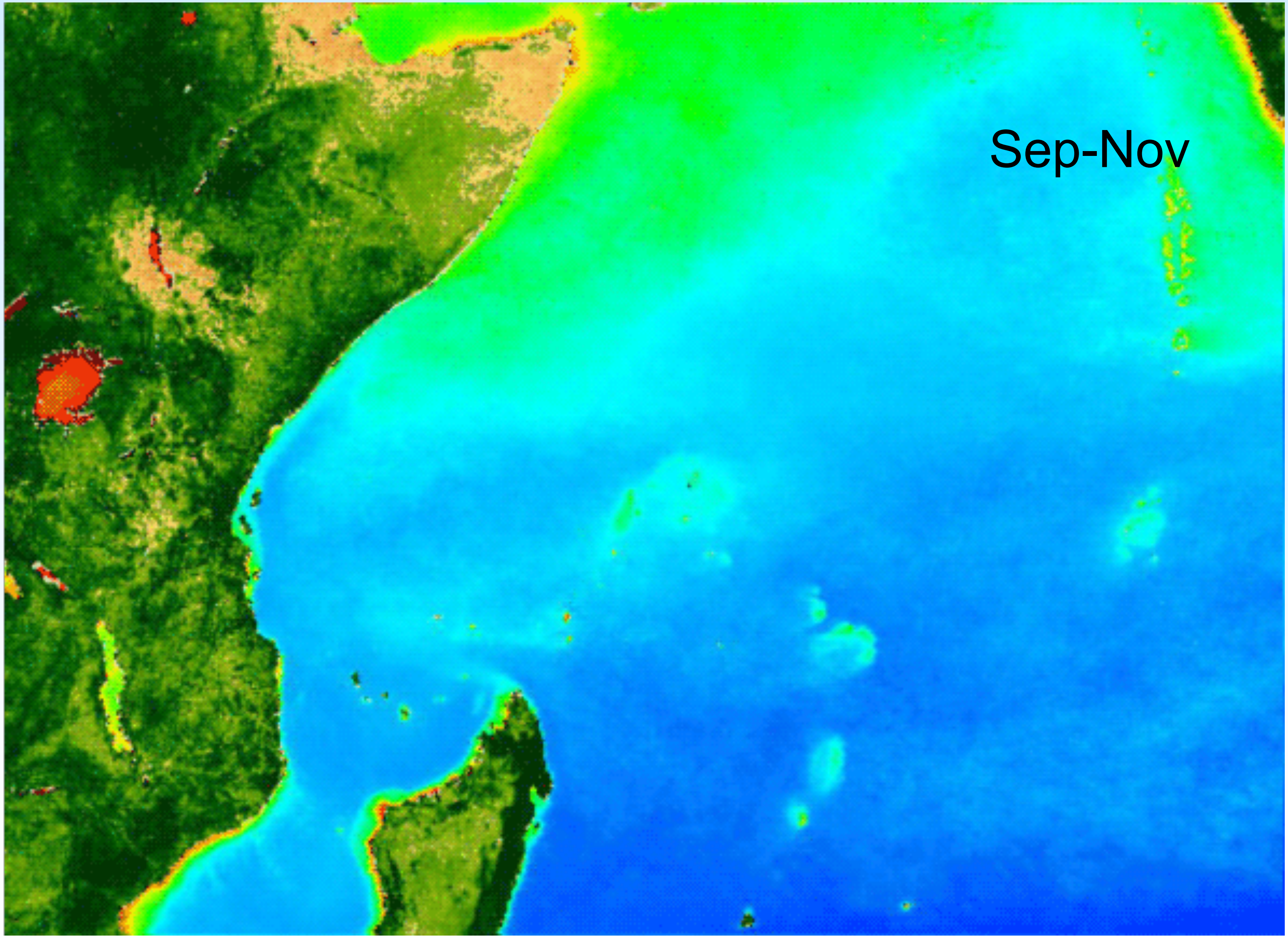

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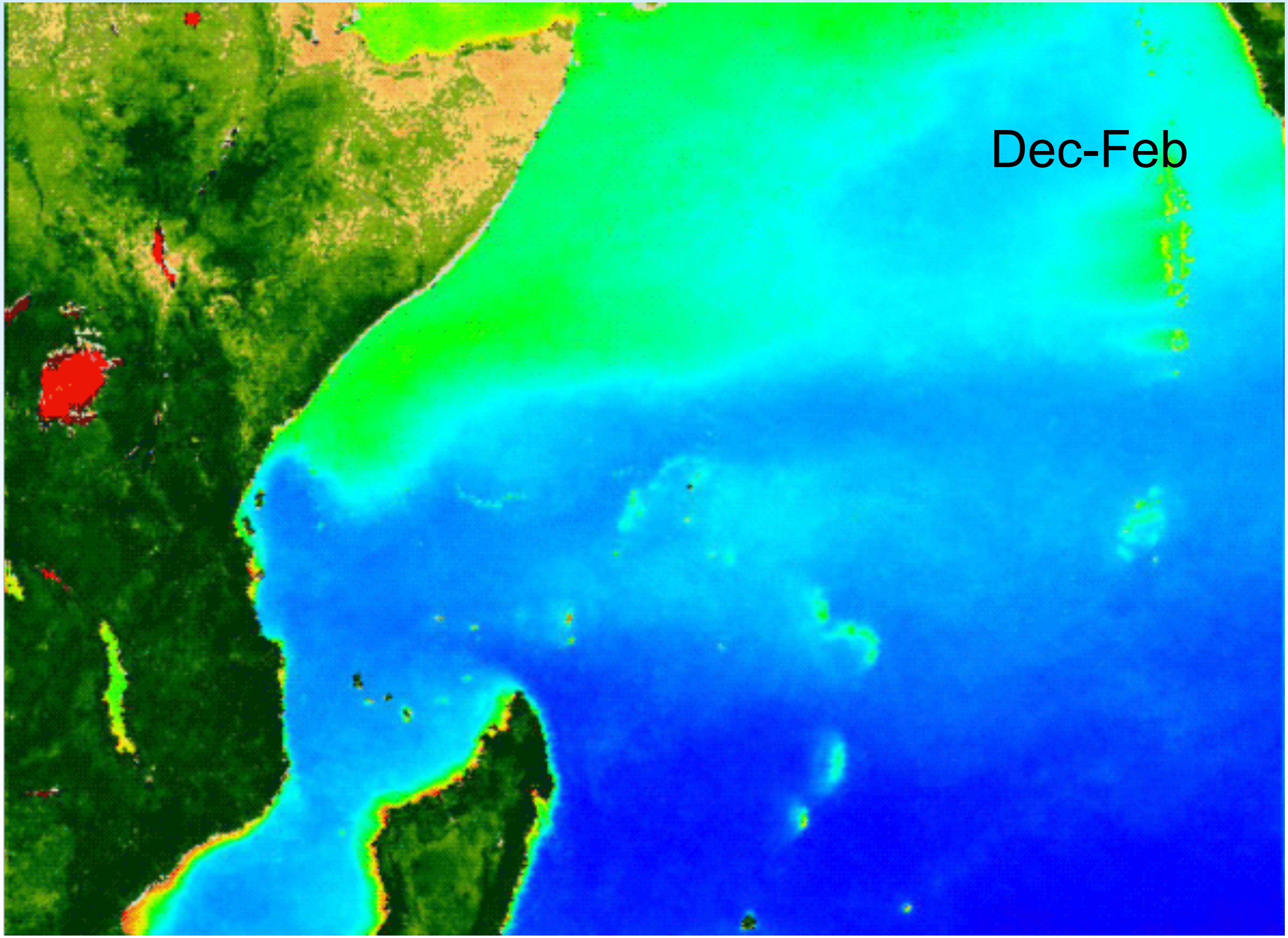
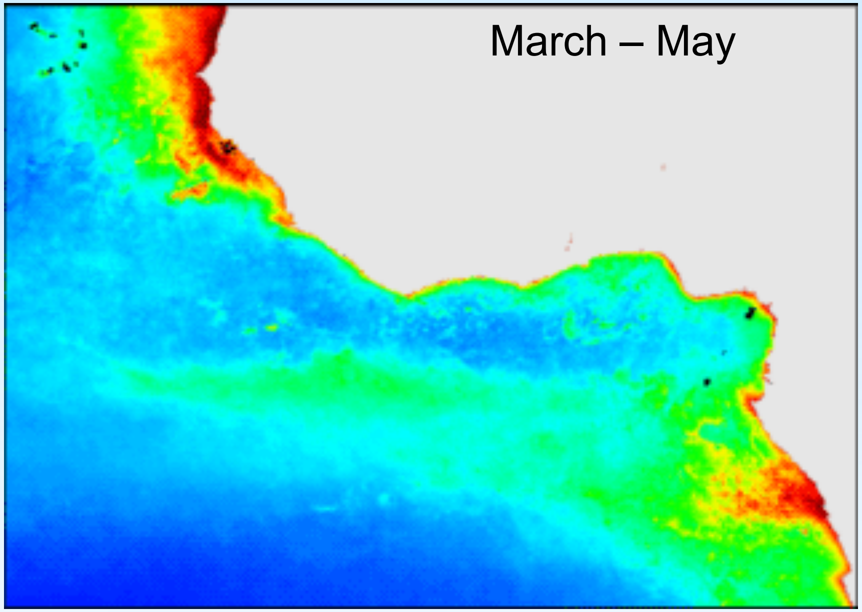
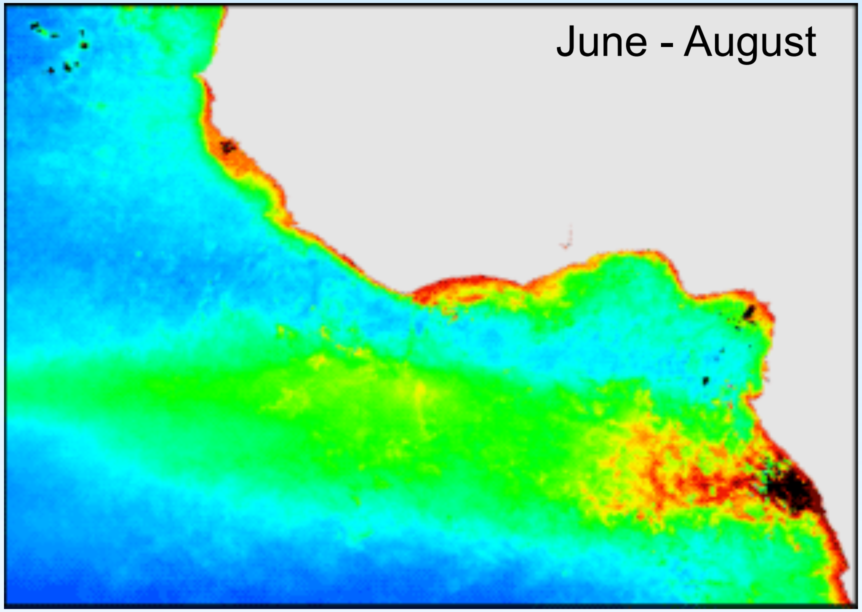
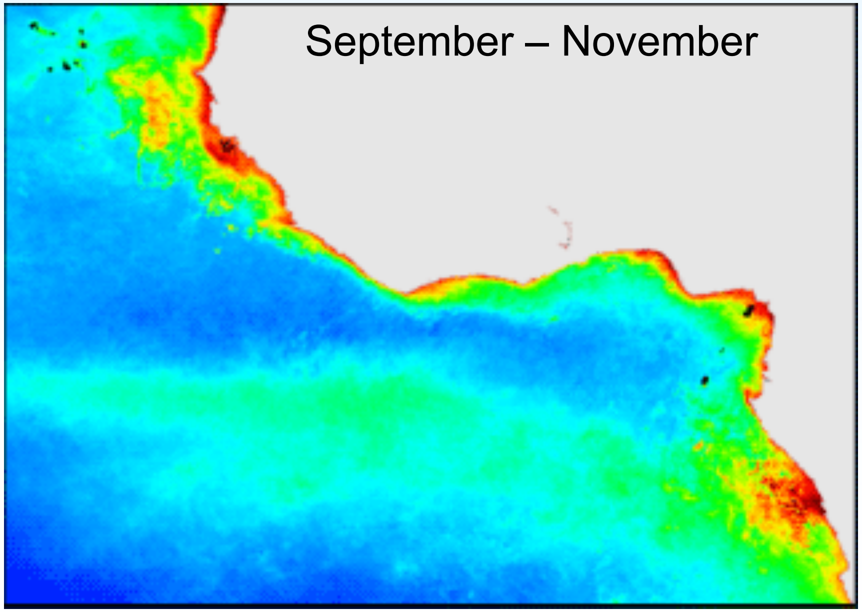
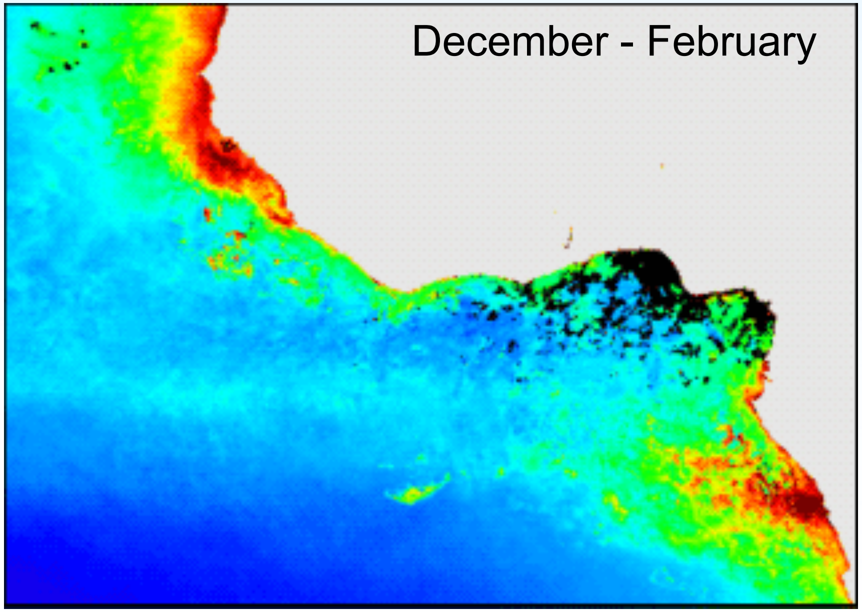


Seasonal chlorophyll climatology (MODIS)









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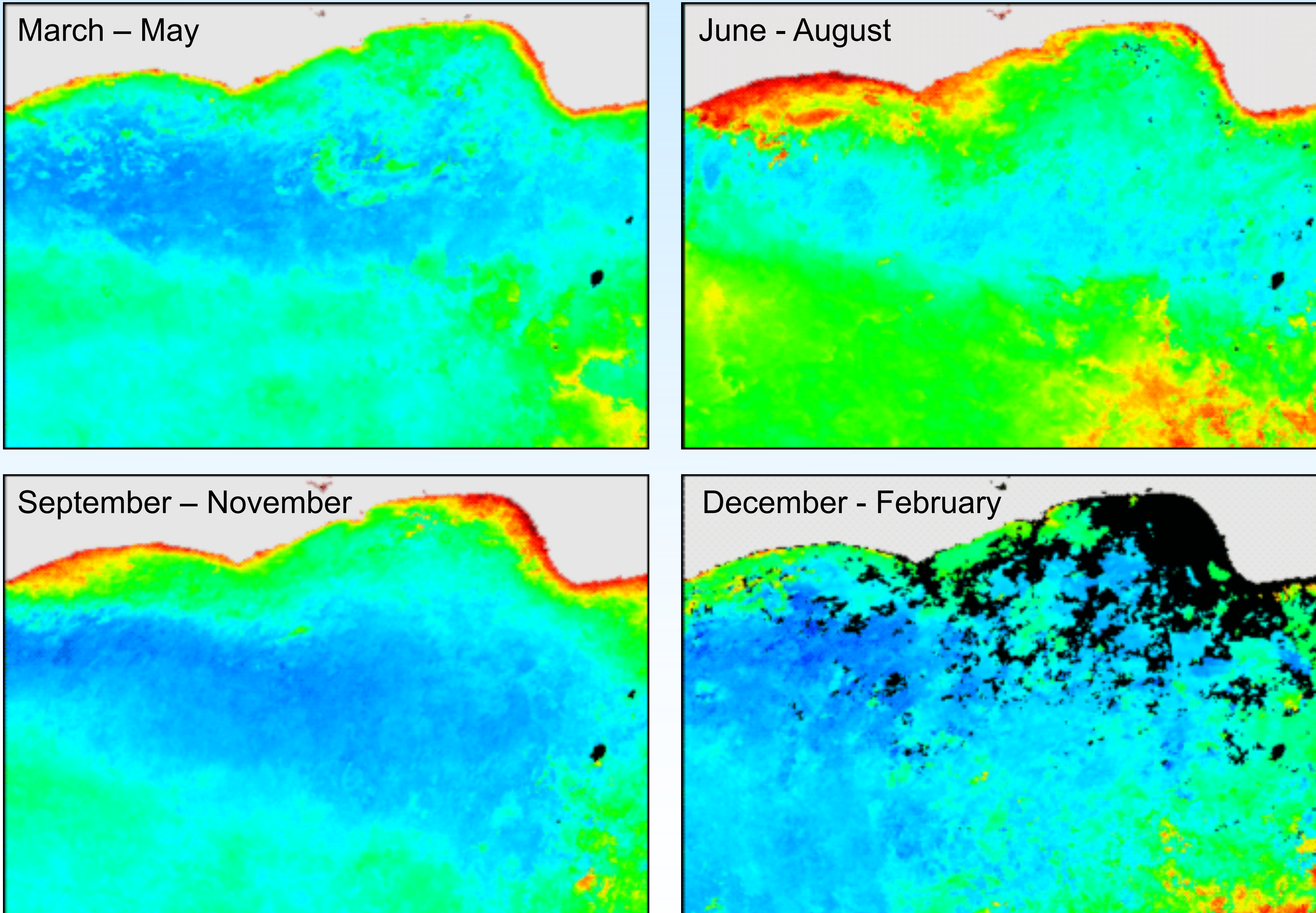


The diffuse attenuation coefficient K_d

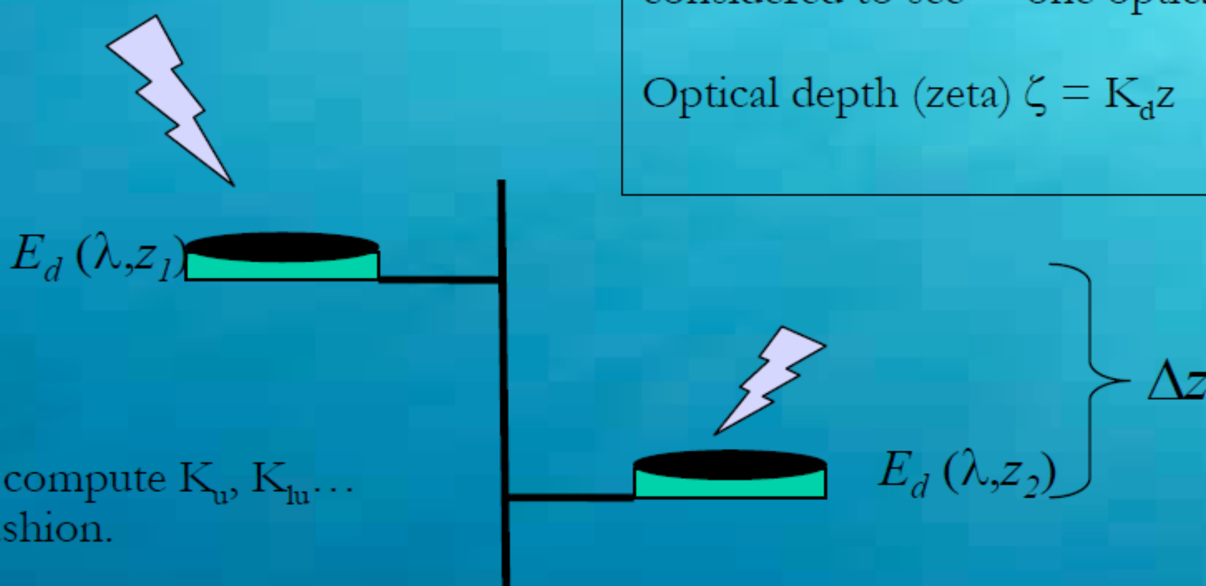
In-water measurement

Courtesy of Stewart Bernard, CSIR

K_d is valuable because it tells us how the light field changes with depth, important to understand the depth of the euphotic zone or for production modelling. A satellite is considered to see ~ one optical depth, where:

Optical depth (zeta) $\zeta = K_d z$

We need to measure the vertical profile of the downwelling irradiance.

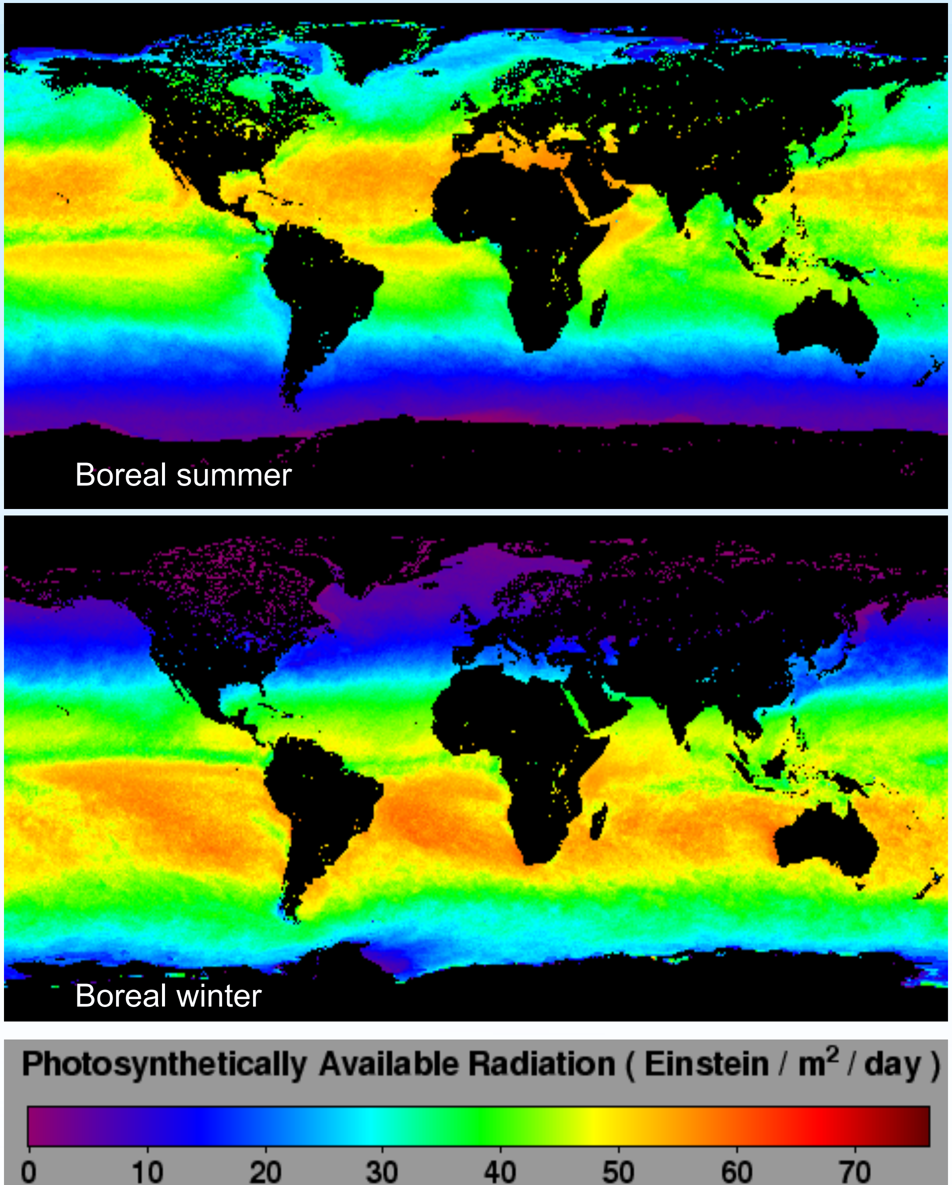


We could also compute K_u, K_{lu}… in a similar fashion.

K_d is also called a quasi-inherent optical property, because it is possible to relate it to constituent concentrations over limited concentration ranges and illumination conditions. Units m^{-1} . **NOTE: K $\neq$ c**

$$-K_d(\lambda, z) = \frac{1}{\Delta z} \ln\left[\frac{E_d(\lambda, z_2)}{E_d(\lambda, z_1)}\right]$$

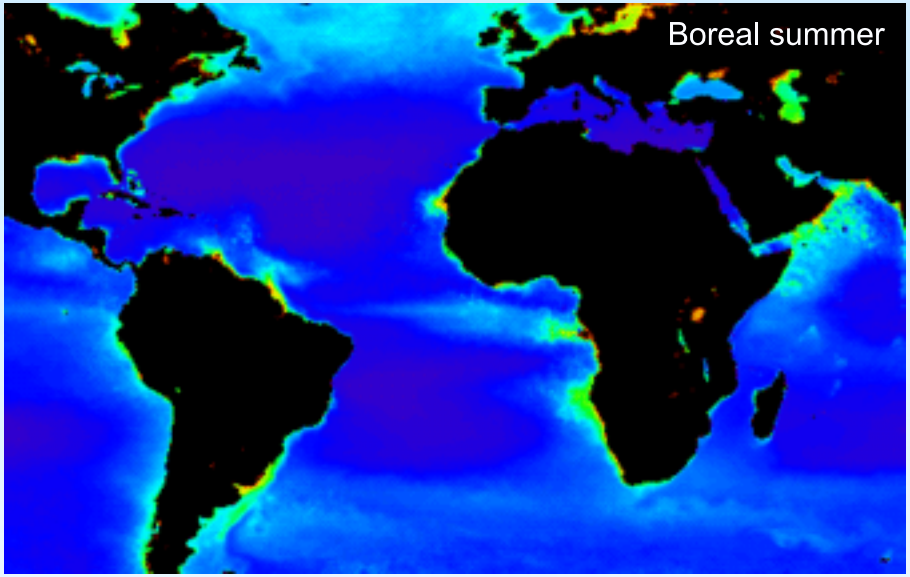
PAR (Photosynthetically Active Radiation)

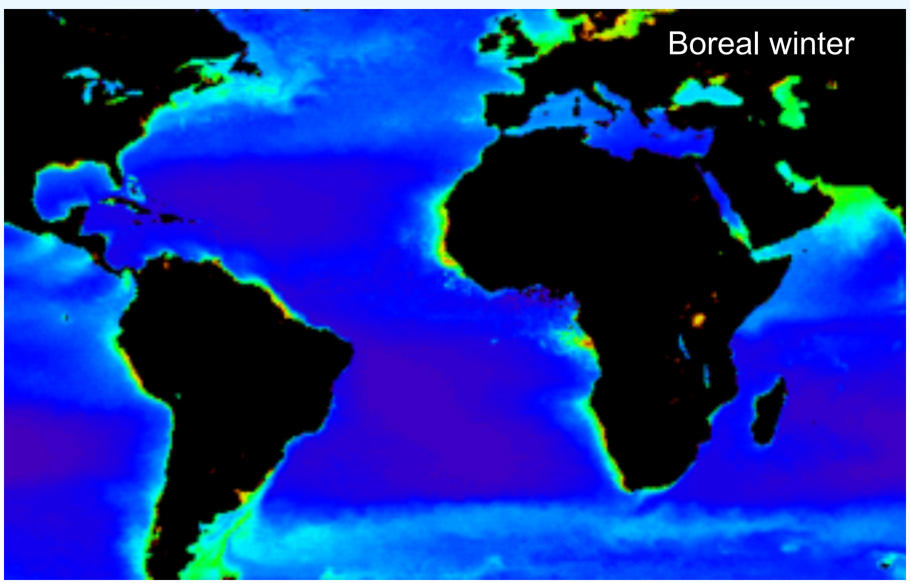


- Definition:
  - Downwelling irradiance in the wavelength interval 400-700nm immediately below the surface
- Units:
  - Einstein m^{-2} day^{-1}
    - or W m^{-2} day^{-1}
- Available product from:
  - SeaWiFS. MODIS. MERIS
  - Satellites measure IPAR
    - Instantaneous PAR at overpass
    - PAR is calculated from this using daylength, sun angle, cloud cover data etc.
- Used in calculations of primary productivity

Not included in the EAMNet data

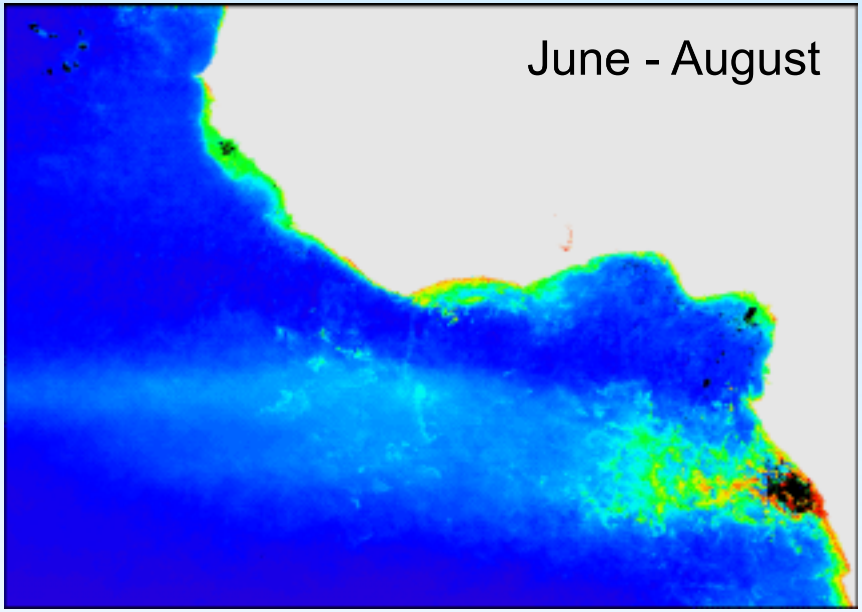
Diffuse attenuation from satellites : Kd 490

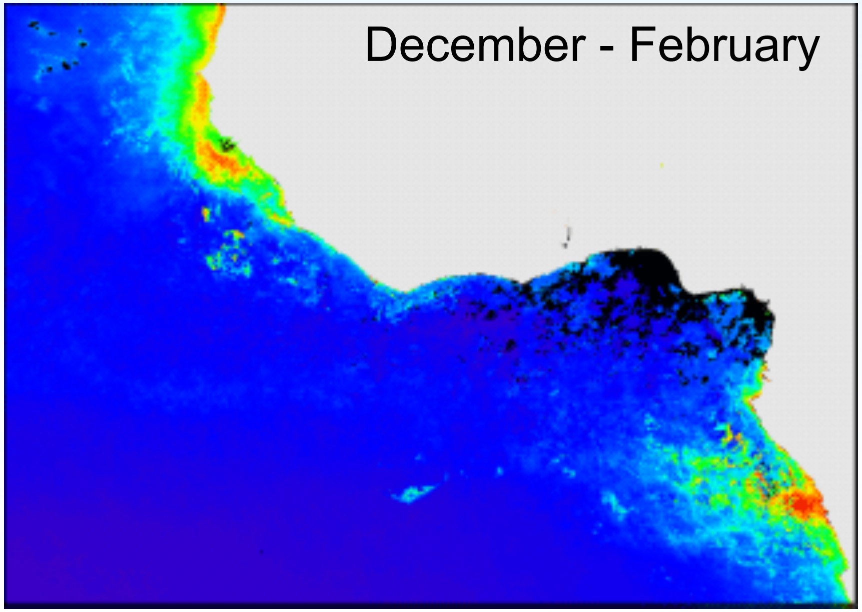




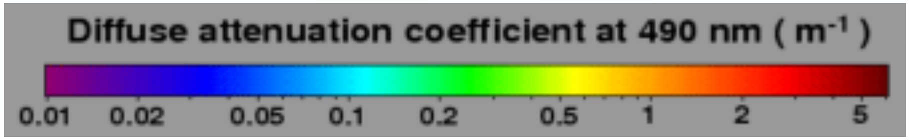
- Derived from blue (490) : green (~547) reflectance ratio
  - Empirical polynomial function based on in-situ / satellite match-up data
- Unit: m^{-1}
- Surface concentrations only
- Standard product from:
  - SeaWiFS (1997-2010)
  - MODIS Aqua (2002-present)
  - Can be calculated from MERIS reflectances (2003 – present)

Applications of Kd 490





- Index of water clarity
  - Representative of surface waters to 1 optical depth τ = 1/Kd490
- Used in calculations of
  - Light penetration to depth
    - Euphotic zone depth ~ 4.6 * 1/Kd
  - Primary production as a function of light available at depth
  - Under-water visibility
  - Water depth (in shallow water) – along with bottom albedo

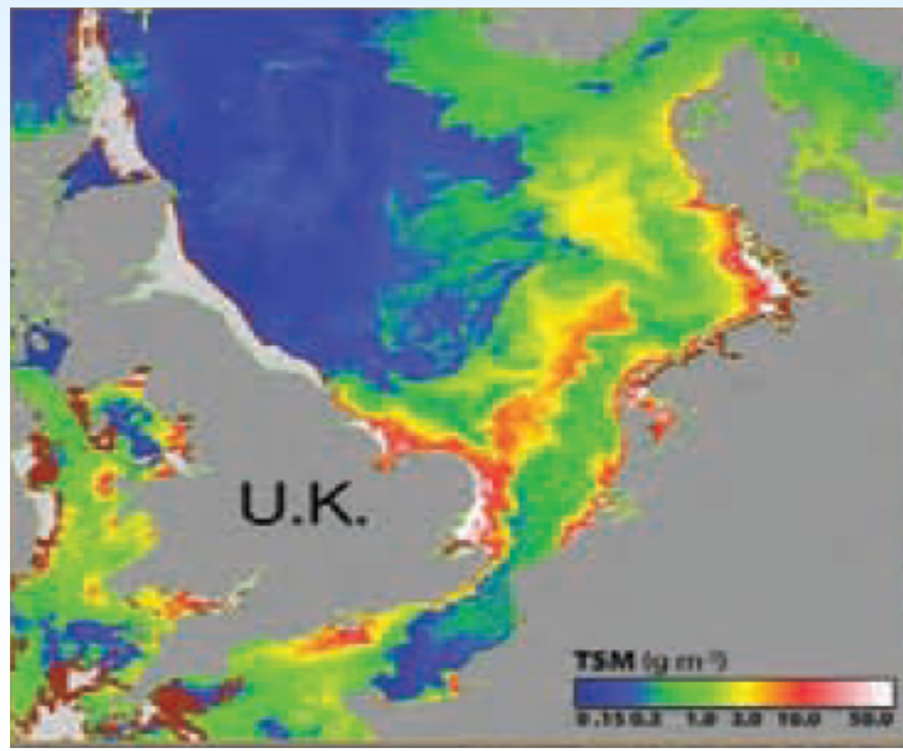


Suspended sediment and CDOM

Suspended particulate matter (sediment)

- Inorganic particulate material
  - Brought into suspension by waves and bottom currents
    - Shallow regions and regions with strong tides
  - Carried into lakes or coastal water by rivers
- Reduces water clarity
- Changes spectral reflectance
  - Increase scattering at all wavelengths – incl. red/NIR
  - Spectral reflectance varies depending on particles
    - E.g. white coral sand differs significantly from particles of brown or red soil

- Suspended particulates is a standard MERIS product
  - derived simultaneously with CDOM and chlorophyll by the Case 2 water algorithm



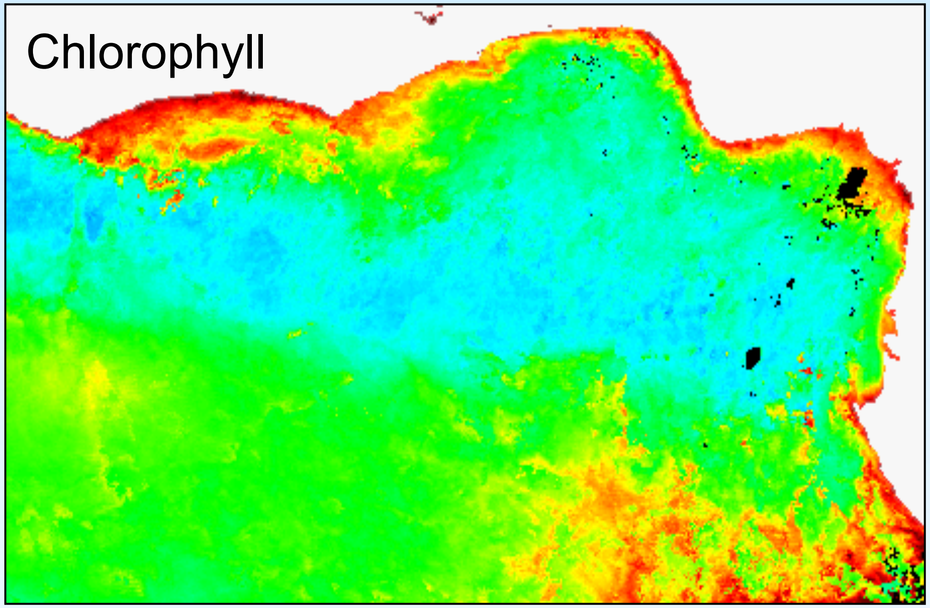
Total suspended matter (SPM) in the North Sea,
Image bu R. Doerffer, IOCCG Report 7 brochure

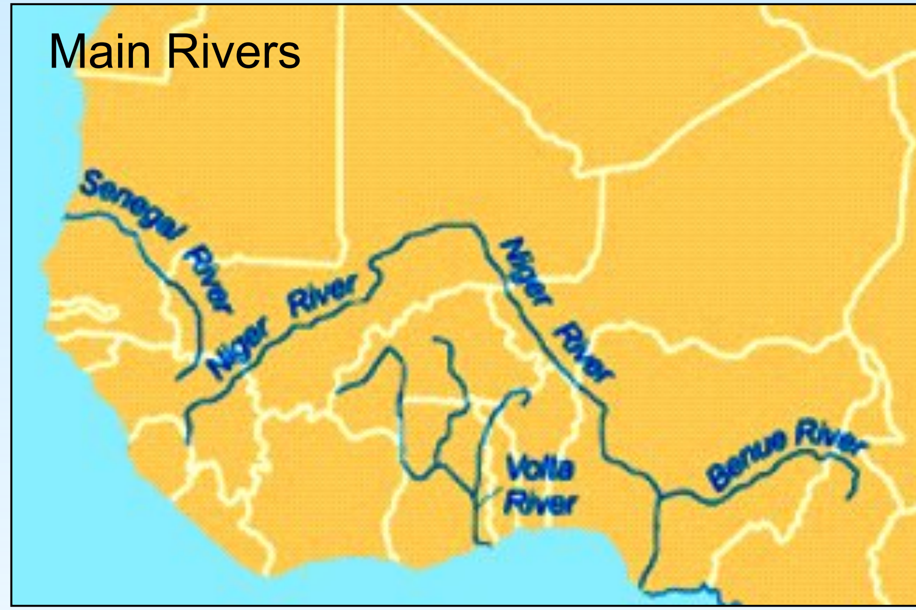
CDOM

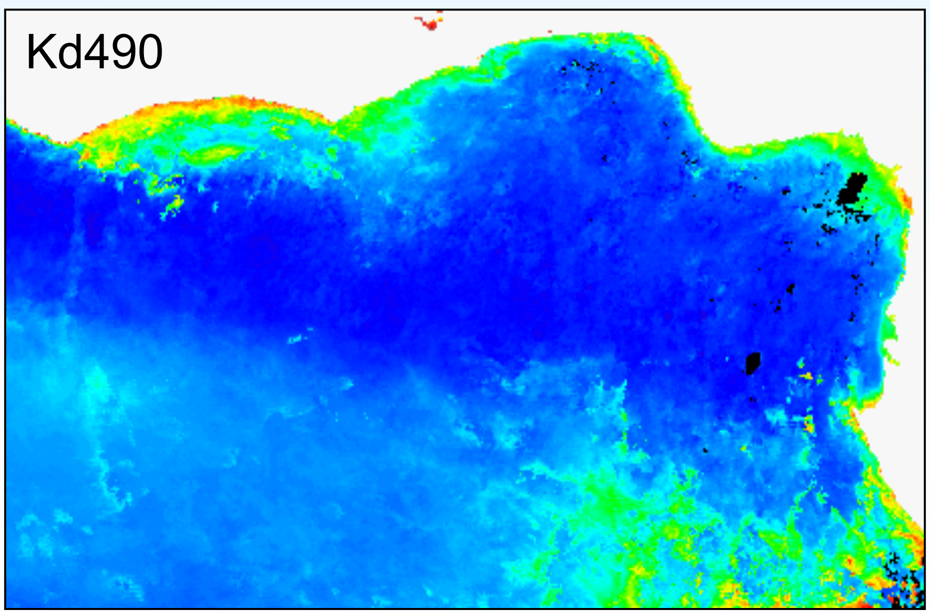
Chromophoric/Coloured Dissolved Organic Matter also known as 'yellow substance' or 'gelbstoff' or gilvin

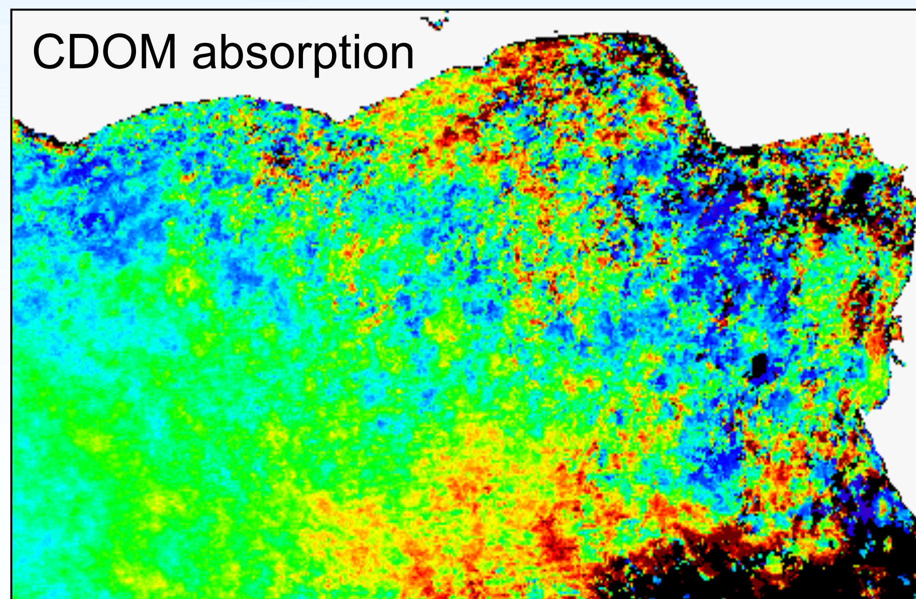
- Organic, dissolved substances
  - humic and fulvic acids
    - local origin - e.g. degradation of phytoplankton cells
    - advected from a distant source – e.g. rivers that flow through heavily-wooded regions and organic-rich soils accumulate a load of CDOM
- Higher load where land run-off is the main source
- Undergoes photo-degradation in surface waters

Gulf of Guinea seasonal climatologies June - August









Examples of ocean colour applications

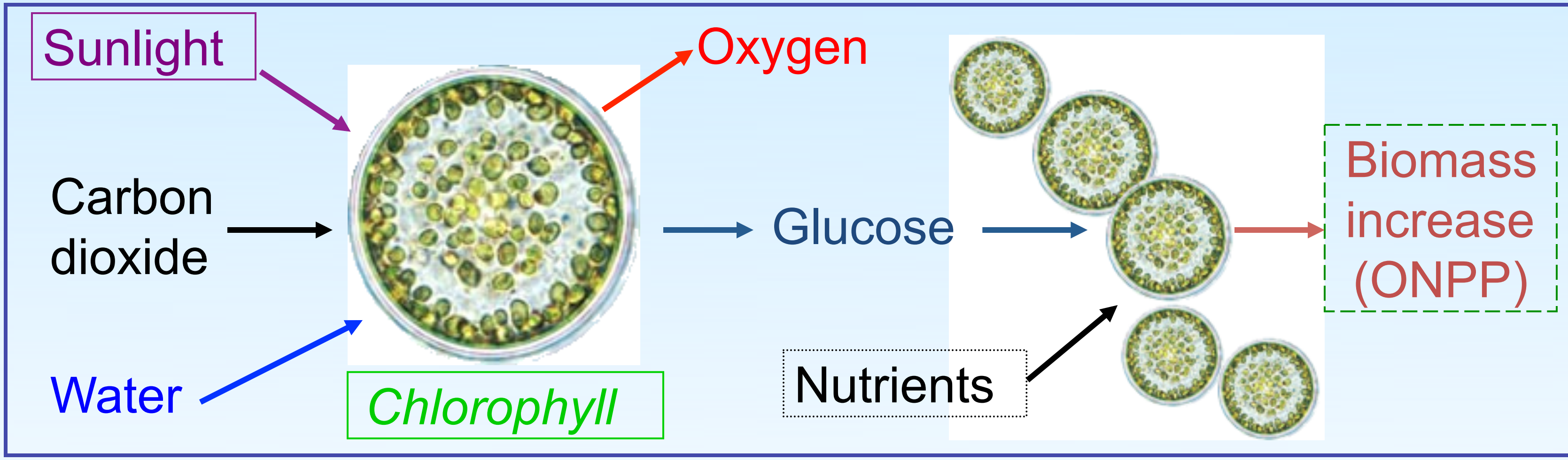
Use of ocean colour in numerical models

- Three different but related uses for satellite data combined with numerical models:
  - Using the model to improve scientific understanding of physical ecological or biogeochemical processes
  - Support for operational monitoring (e.g. for fisheries management, management of coastal/marine ecosystems)
  - Modelling carbon uptake as part of climate change modelling.
- See also IOCCG Report 7, Chapter 2.

Improving scientific understanding

- Needed to answer today's key scientific questions
  - Carbon cycle /climate change; ecosystem studies
- Investigate complex interactions between many parameters
  - Chlorophyll shows only when a bloom occurs; understanding of the processes involved understanding requires modeling
- Ecosystem modelling with N-P-Z models:
  - Balance between primary production (P), nutrient supply (N) and grazing by zooplankton (Z)
  - Embedded in a physical/dynamical model describing circulation, mixing and upwelling.
- Comparison with satellite data from many different sensors to assess (validate) the model results
- Modelling essential to understand complex coastal areas

Modelling Ocean Net Primary Production



A depth integrated model:

$$\Sigma PP = P^{B}_{Opt}\, f\,(PAR)\,(Chl\text{-}a)\,(Z_{eu})$$

Primary production

Max carbon fixation rate

Photosynthetically active radiation

Surface chlorophyll

Depth of euphotic zone

Modelling Ocean Net Primary Production

$$\Sigma PP = P^{B}_{Opt}\, f\,(PAR)\,(Chl\text{-}a)\,(Z_{eu})$$

Primary production | Max carbon fixation rate | Photosynthetically active radiation | Surface chlorophyll | Depth of euphotic zone

- PAR estimates
  - Ocean colour algorithms give IPAR (Instantaneous PAR)
  - Used to compute daily PAR
- Surface chlorophyll
  - Variety of algorithms
    - Give different absolute values
  - Error <35% globally
    - except along coasts, Antarctic, coastal upwelling regions
- Depth integrated chlorophyll
  - Euphotic depth (Z_{eu}) modelled from chlorophyll / diffuse attenuation, Kd
  - Chlor-a and Kd both RS parameters
- Max carbon fixation rate $\mathbf{P^{B}_{Opt}}$
  - Not available from remote sensing
  - Varies regionally with light regime, species assemblies

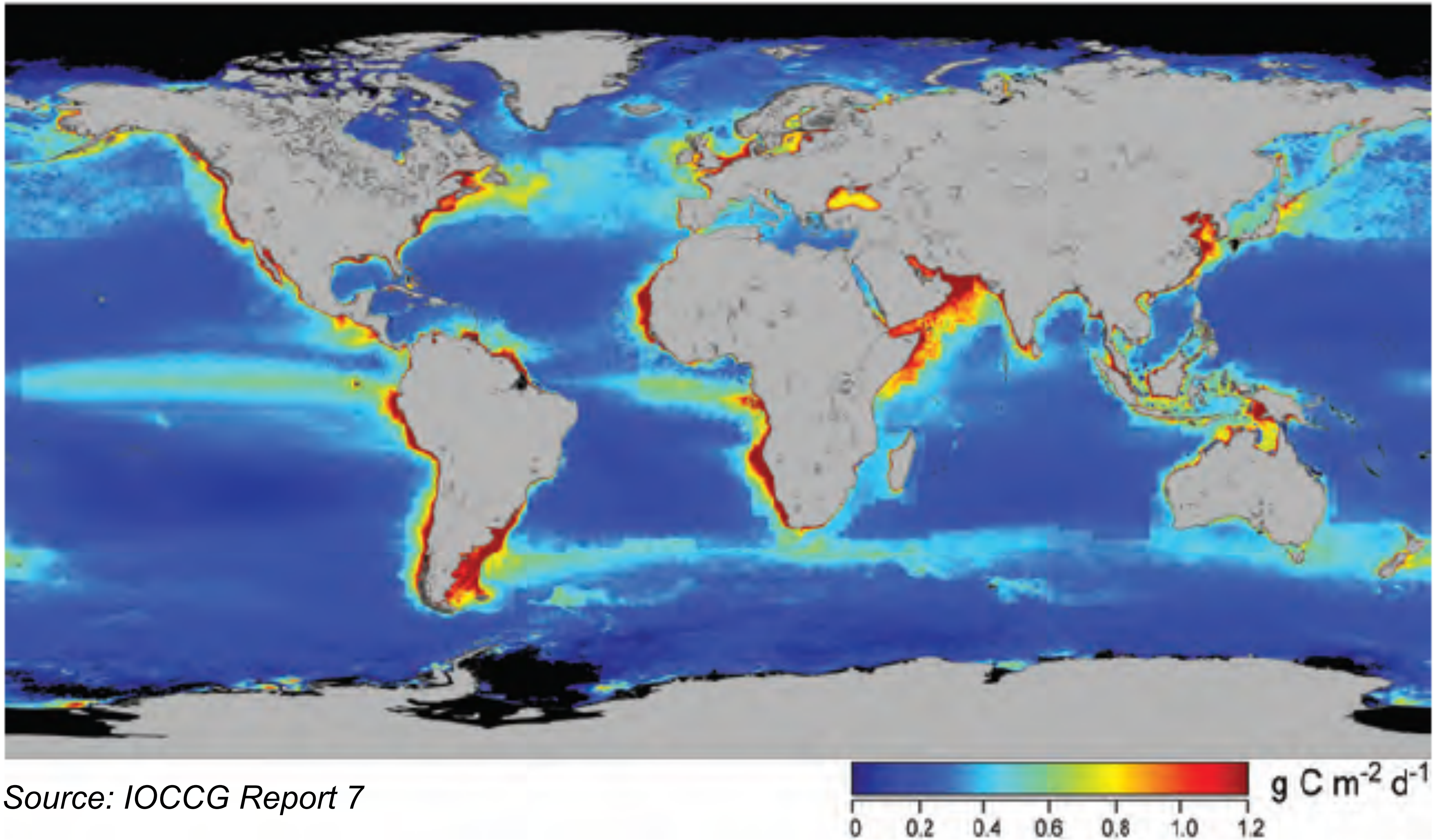
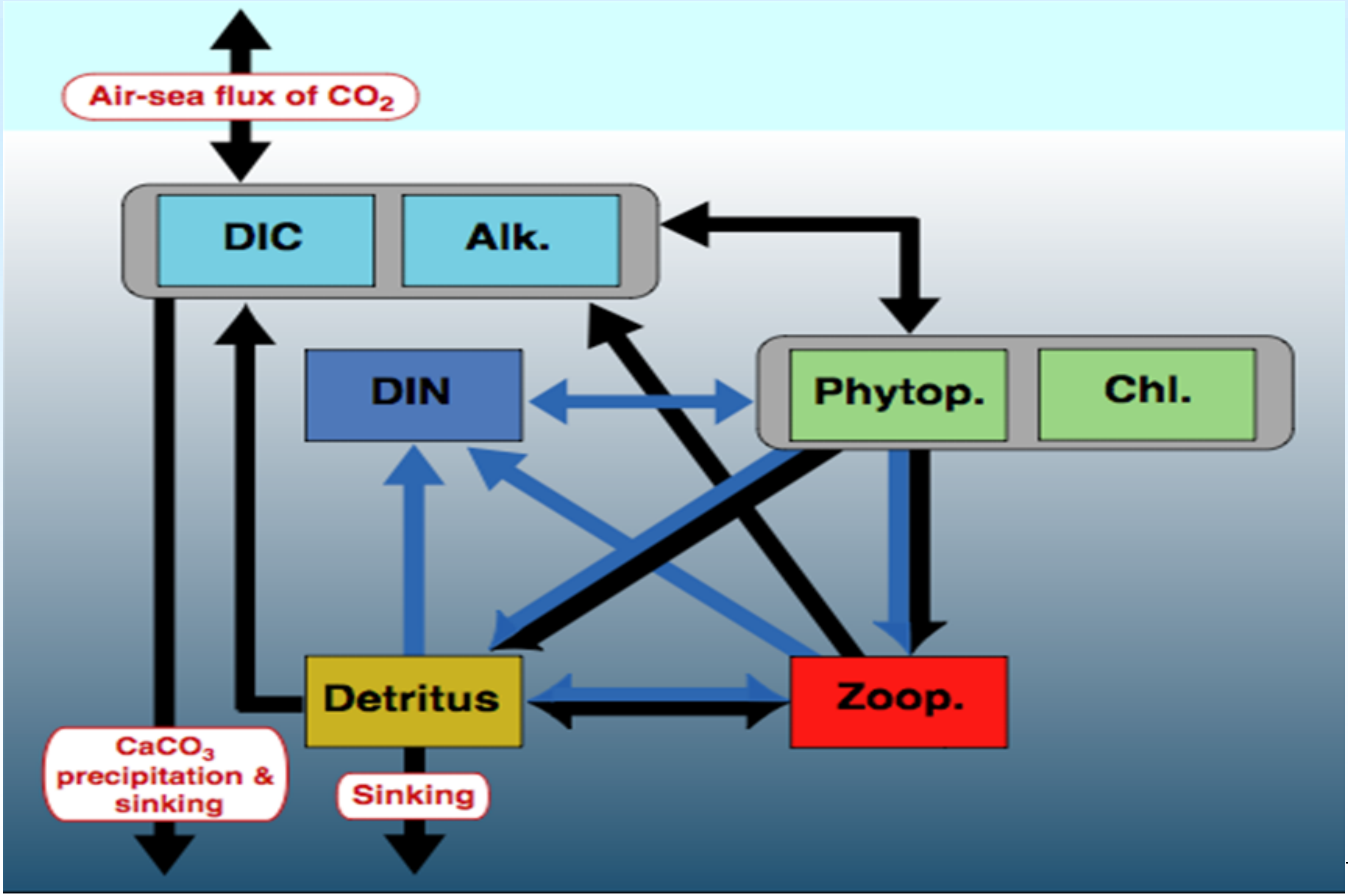
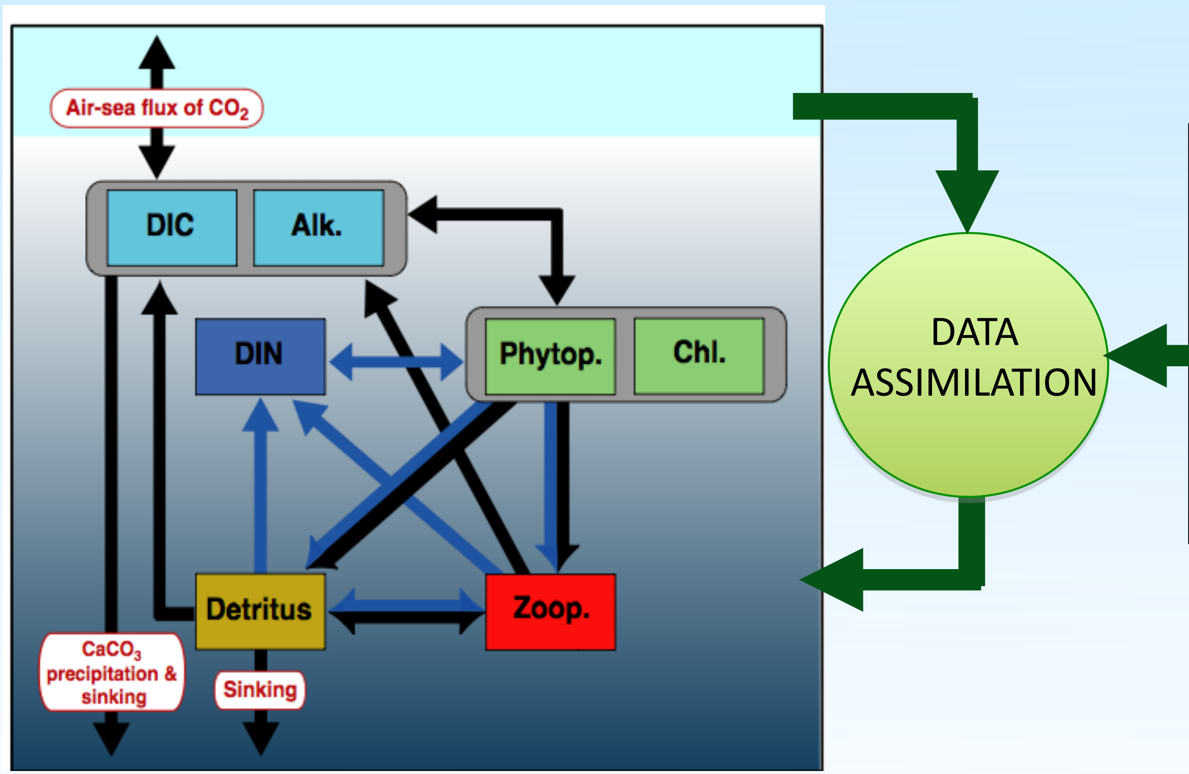


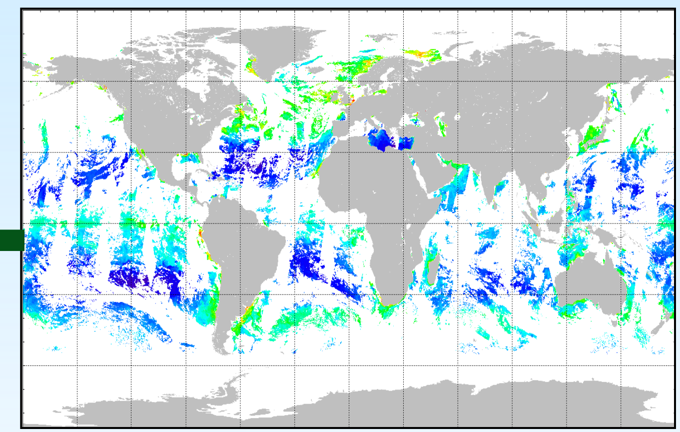
Figure 5.4 Global primary production computed using MODIS-Aqua data from July 2002 to June 2005 with a wavelength, depth-resolved, primary production model down to the 0.1% light-level. (Credit: Frédéric Mélin, Joint Research Centre, EC, unpublished data. MODIS data provided by NASA/GSFC).

Modelling the ocean carbon cycle



Assimilation of Daily Chlorophyll into the HadOCC Model





ACRI & the GlobColour Team

NOC scheme balances nitrogen (blue) and carbon (black) in the UK Met Office assimilation system for the Hadley Centre Ocean Carbon Cycle model

Modelling to meet operational needs

- Examples:
  - Early warning of harmful algal blooms
    - Satellite data can provide early warning without modelling, given cloud free conditions
    - In situ data to provide information about plankton species, toxicity etc.
    - Modelling used to fill gaps and predict bloom evolution and transport
    - Regular update with satellite data when available
  - Water quality monitoring , planning of off-shore operations
    - Radiometry used as a tracer for water movements
    - Medium resolution current information from satellites
    - Assimilation of satellite data into a hydrodynamic model provides predictability and information also in adverse weather conditions
- Operational modelling requires NRT satellite data
  - For scientific studies, accuracy is more important than time, so delayed mode data is used.

Using satellites to study physical dynamics

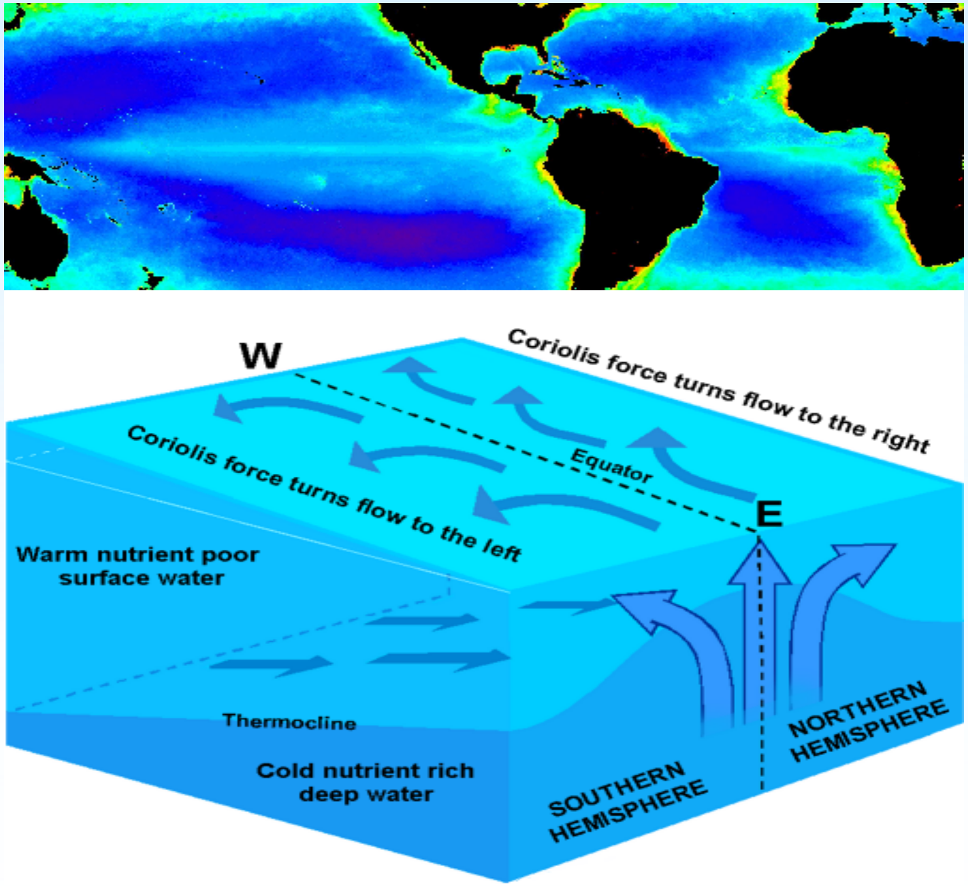
- Best done with a combination of different satellite sensors
  - Satellite altimetry: geostrophic component of the ocean circulation and mesoscale features (e.g. eddies)
    - Cannot be used at +/- 5 degrees N and S of the equator
    - Problematic close to the coast and in water < 50m depth
  - Synthetic Aperture Radar (SAR):
    - Abrupt changes in surface roughness can indicate current boundaries and current convergence.
    - Surface organic films concentrated along lines of current shear provide high-resolution information about current eddies, dipoles, river plumes etc.
  - SST and ocean colour: advection of surface layers by currents
    - River plumes, fronts, unstable meanders, filaments, dipole and monopole eddies and jets

Ocean-Colour Radiometry and Ocean Physics

- Distribution of phytoplankton in the surface mixed layer is intimately linked to physical ocean processes.
  - Current divergence, upwelling and nutrient supply
  - Vertical mixing and water column stability
  - Horizontal advection, diffusion and mixing
  - Penetration of light energy (heating) of surface mixed layer
- Interannual variabilty in ocean currents and temperature lead to interannual variability in plankton productivity
  - El Nino; variations in the position of the Angola Benguela front
  - Variability of tropical Atlantic upwelling
- Suspended particles (sediment and phytoplankton) can act as ‘tracers’ may be used to quantify currents at higher resolution than that available from standard altimetry.

Chlorophyll and the global ocean circulation

Chlorophyll can act as a ‘tracer’ for horizontal and vertical water movement:



Upwelling of deep water:

- Equatorial upwelling zone
- Coastal upwelling areas

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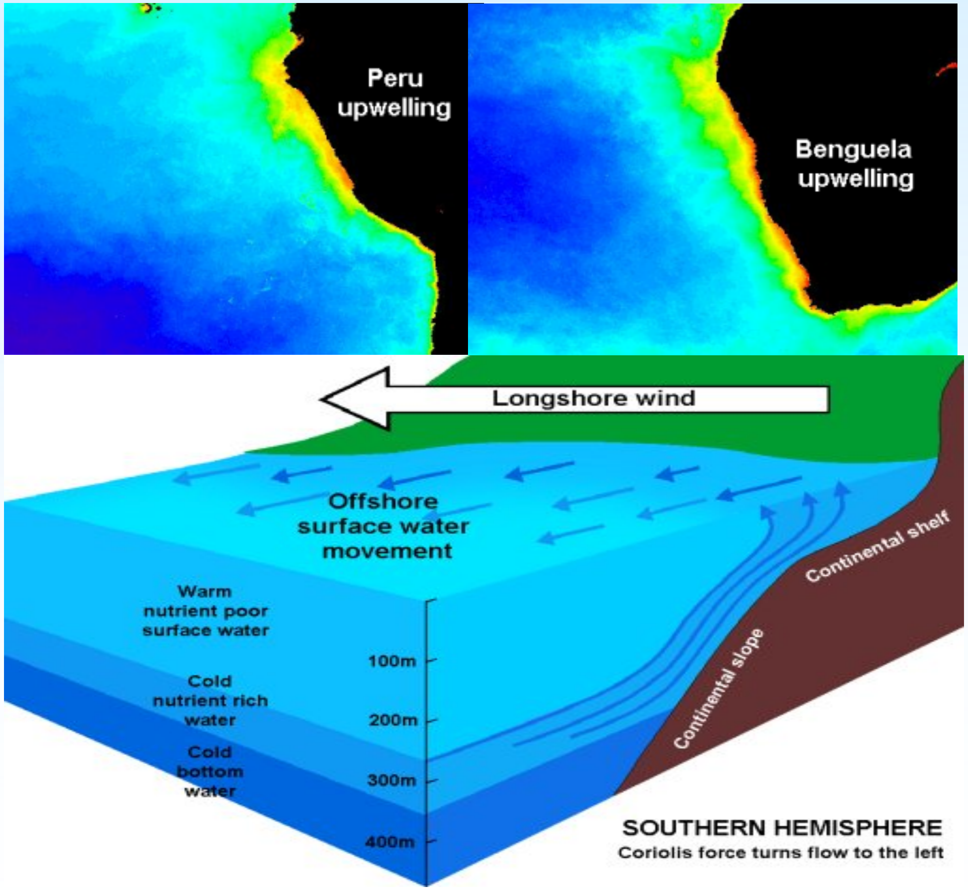

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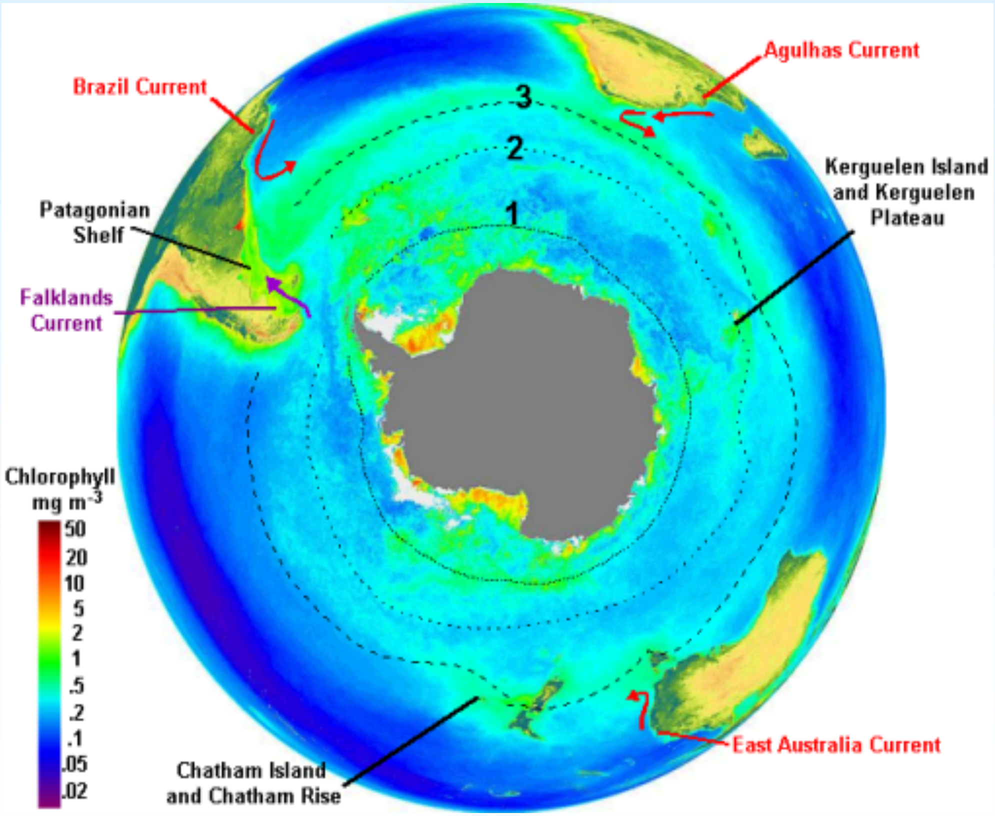

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Fronts between water masses

1. Polar front
2. Subantarctic front
3. Subtropical front

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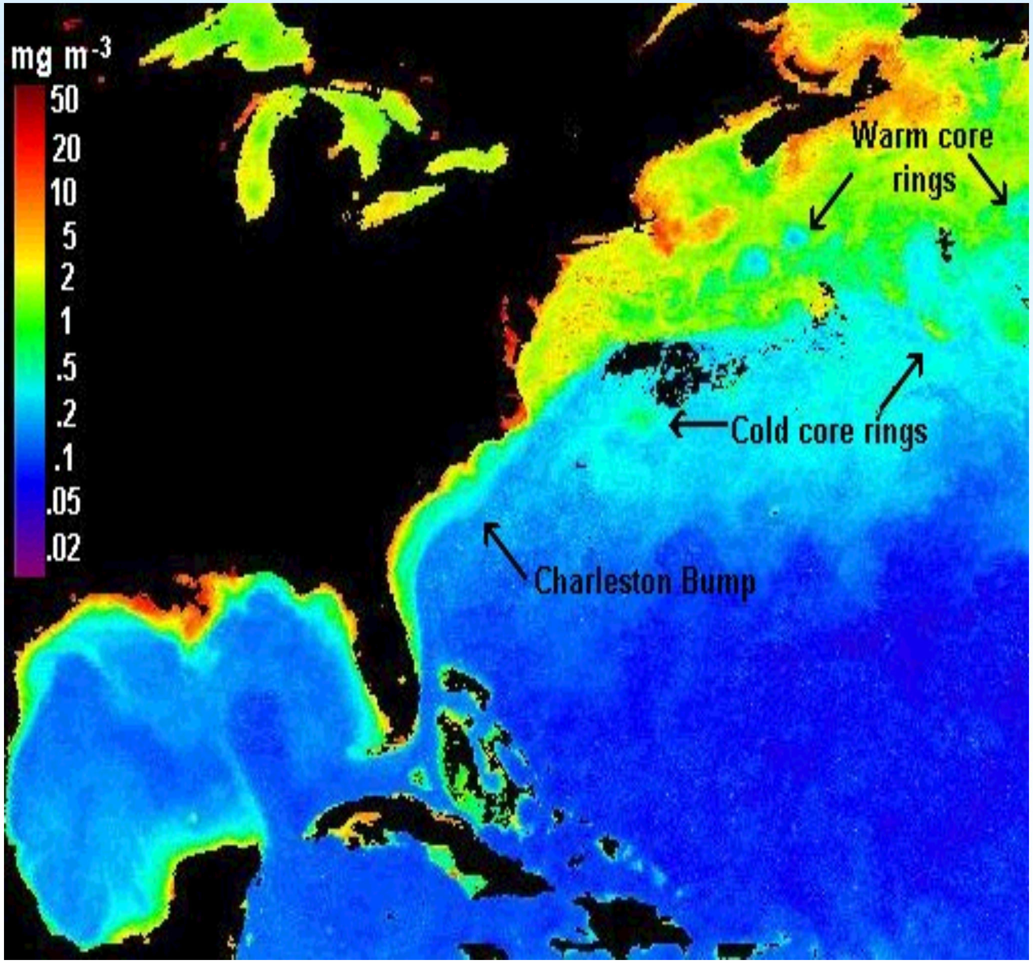

Source: NASA SeaWiFS Project

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Surface currents and eddies associated with

- The Gulf Stream
- Agulhas return current
- East Australia current

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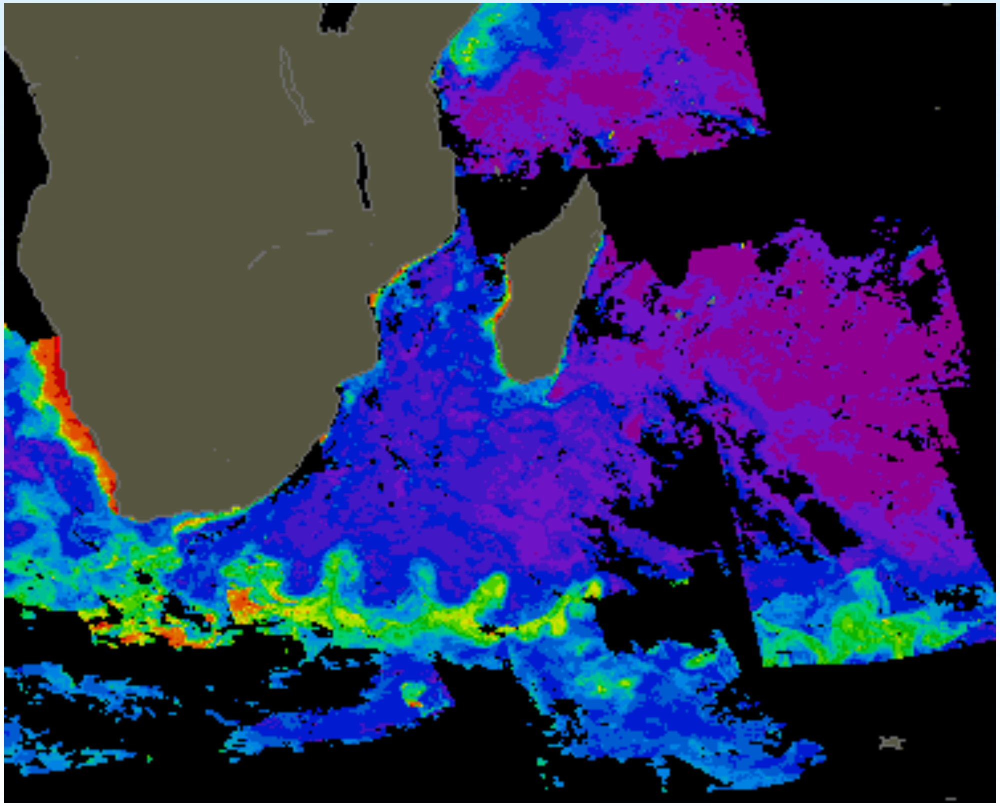

NASA CZCS data

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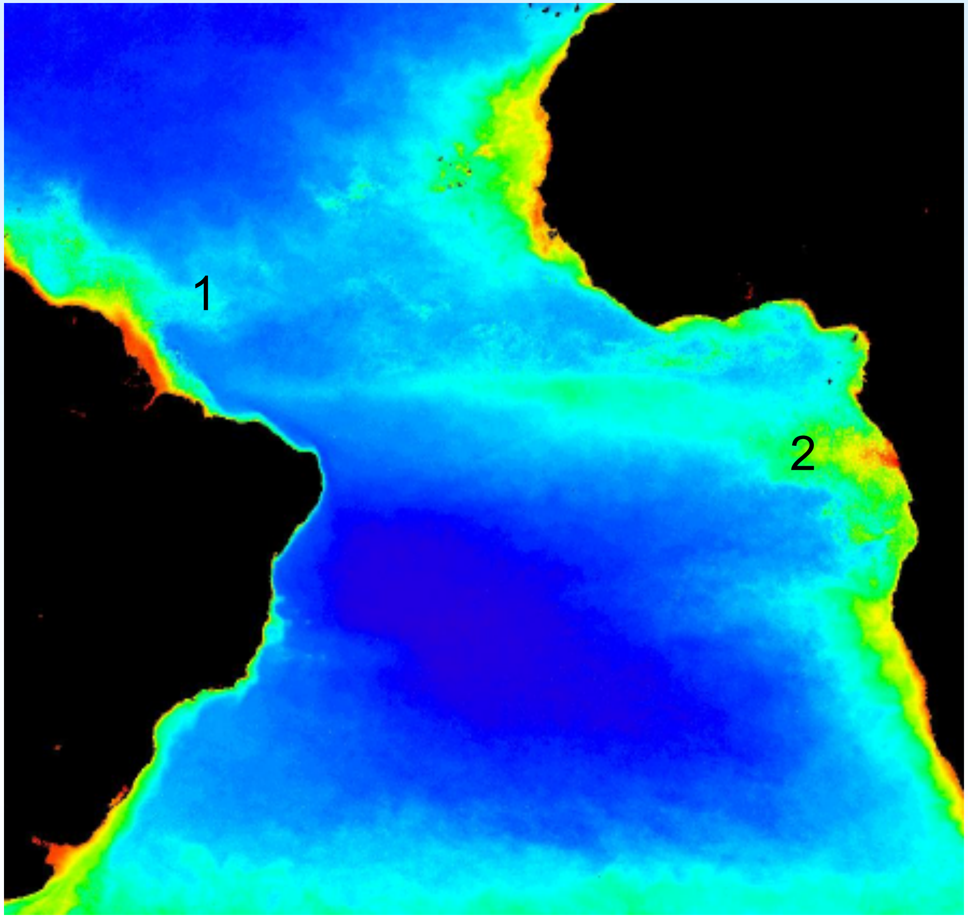

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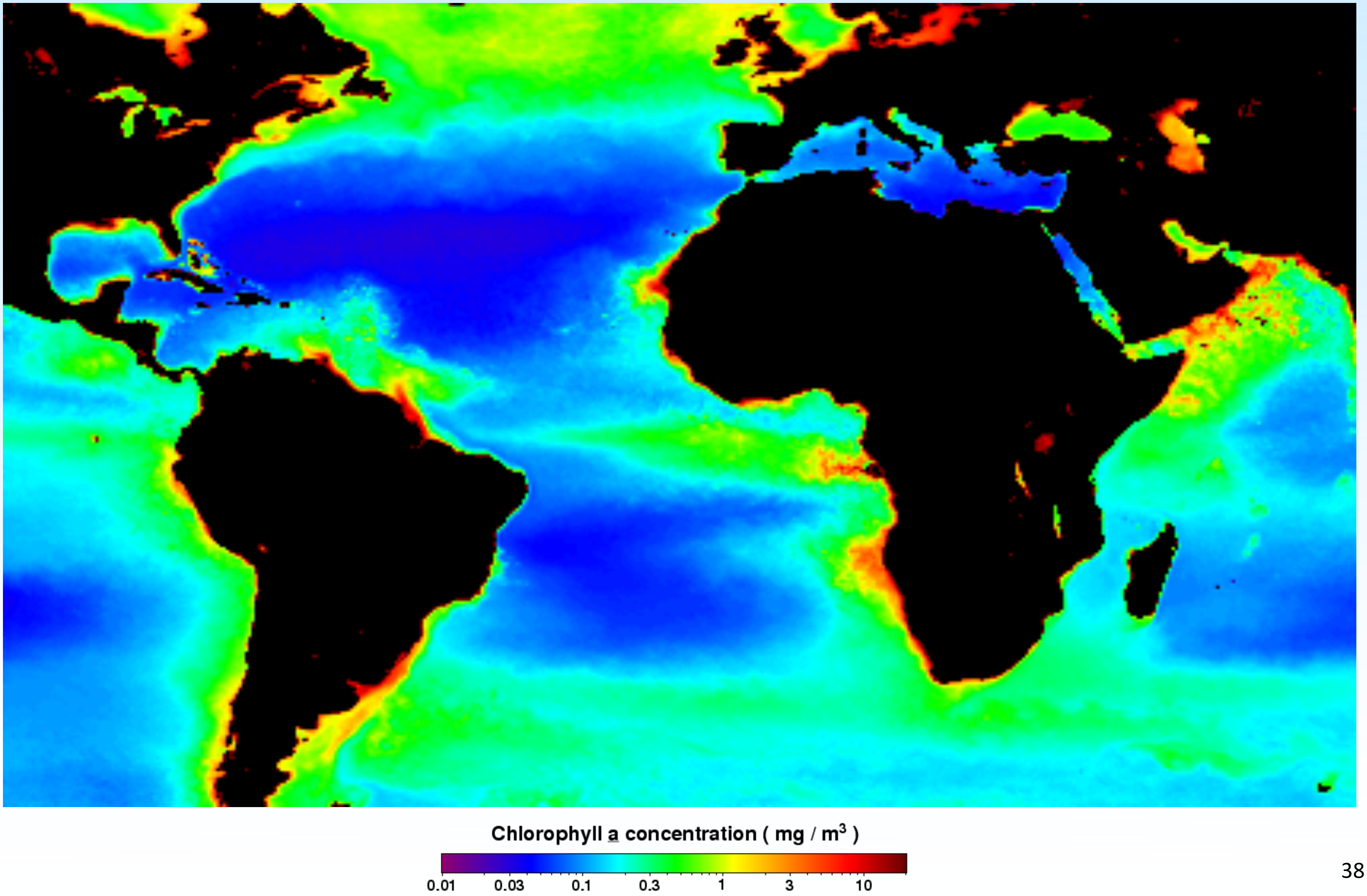
River plumes

- The Amazon (1)
- The Congo (2)

Atlantic: mean annual chlorophyll



Understanding productivity using data from different satellite sensors

GRODSKY ET AL.: EQUATORIAL ATLANTIC UPWELLING AND CHLOROPHYLL

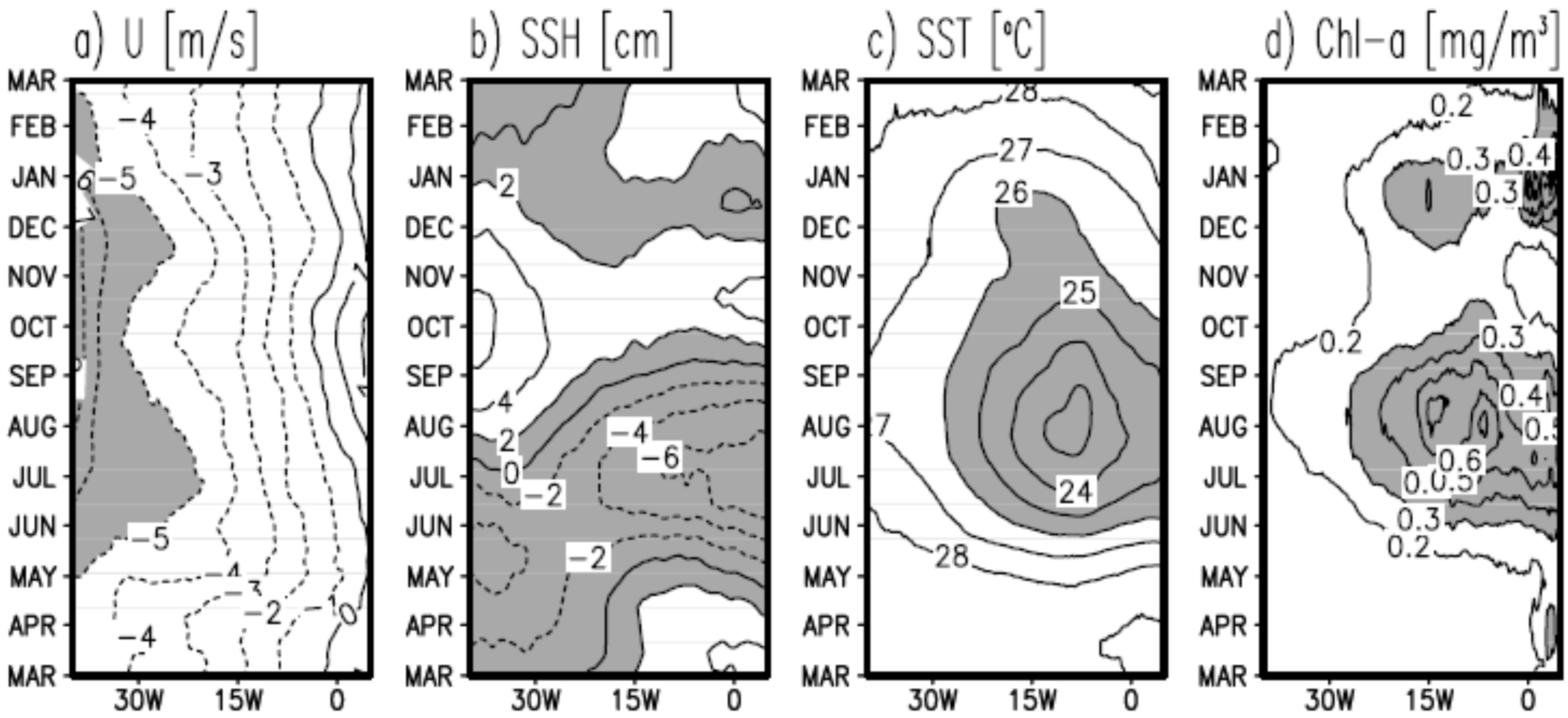
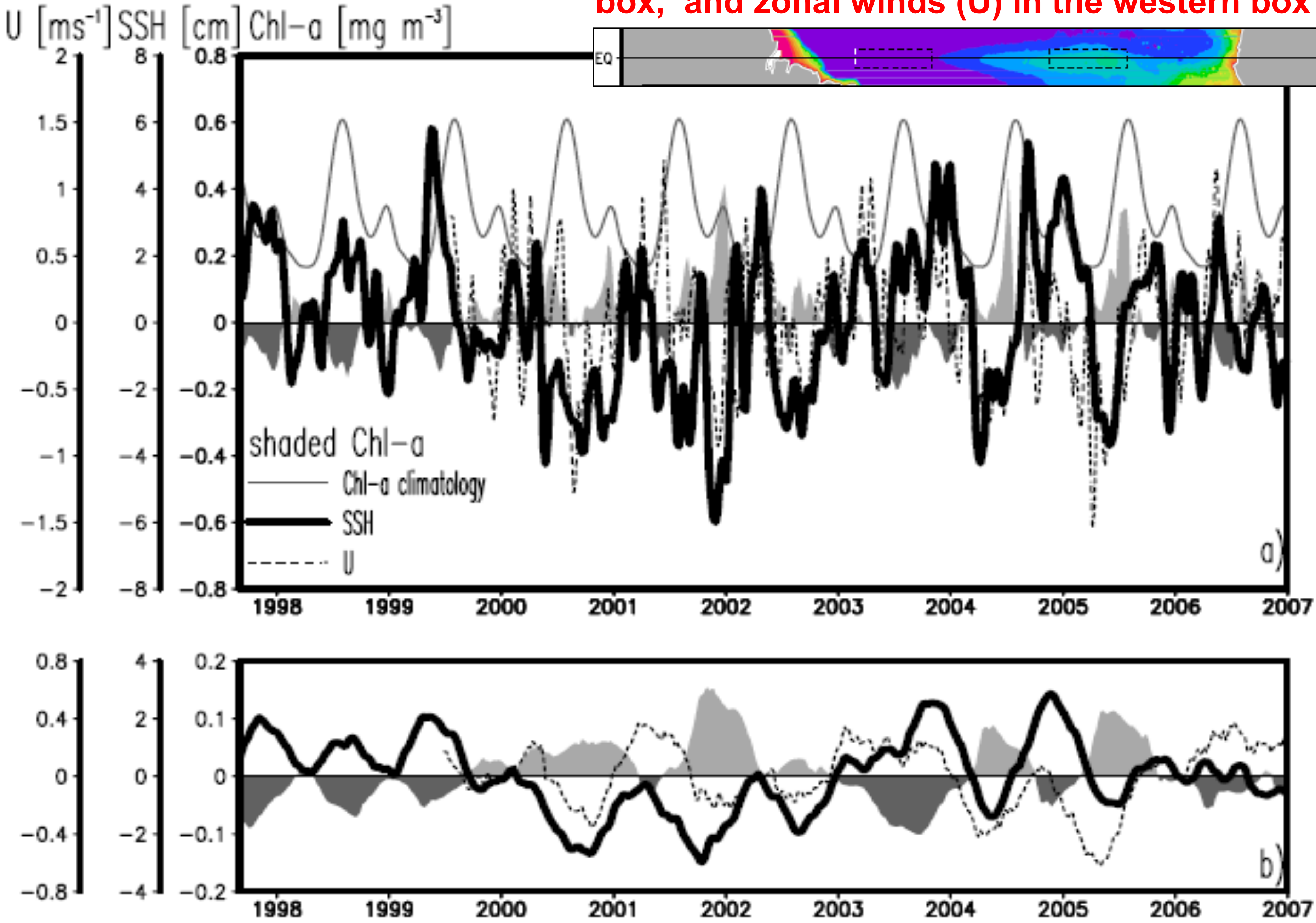
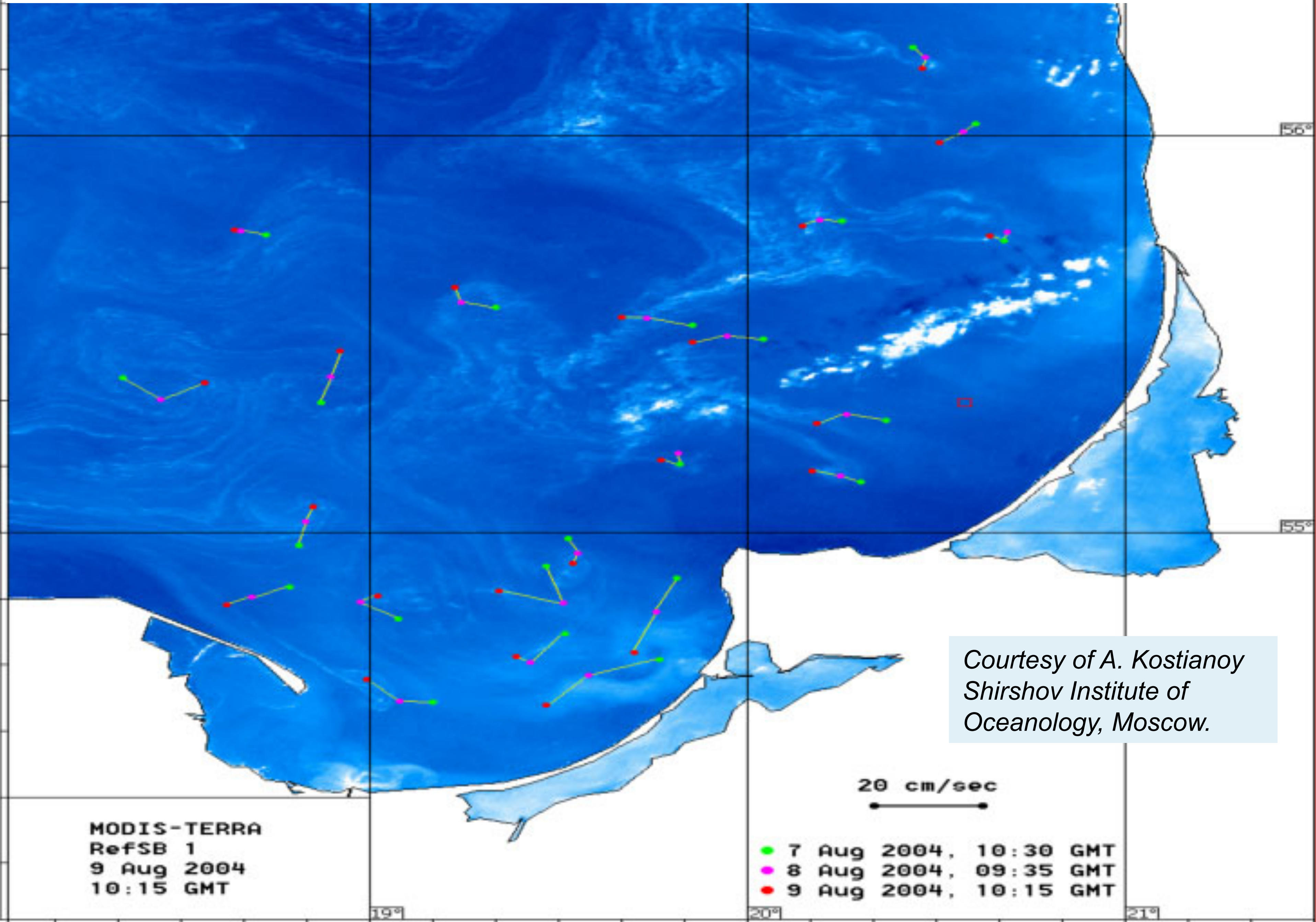


Figure 2. Seasonal cycle of equatorial (a) zonal winds (U), (b) SSH, (c) SST, and (d) Chl-a.

Time series of anomalous Chl-a and SSH in the eastern box, and zonal winds (U) in the western box*.

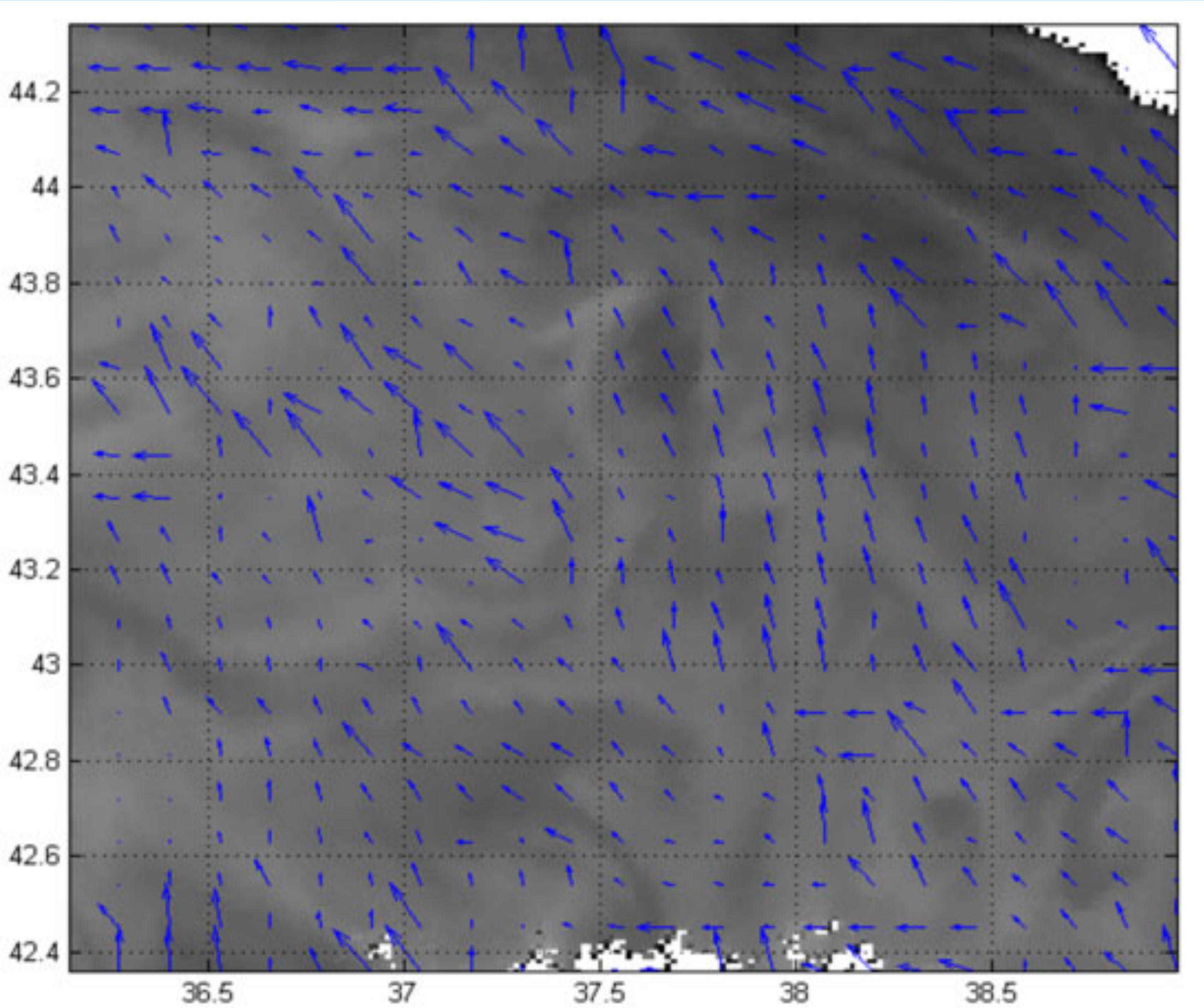


Feature Tracking using Level 1 250m resolution MODIS data



Courtesy of A. Kostianoy Shirshov Institute of Oceanology, Moscow.

Current retrieval using cross-correlation techniques



Surface currents field obtained by mean cross correlation (MCC) analysis for 2 consecutive AVHRR thermal images.

Courtesy of D. Soloviev and S. Stanichny, MHI, Ukraine

Diffuse attenuation (K) and mixed layer depth

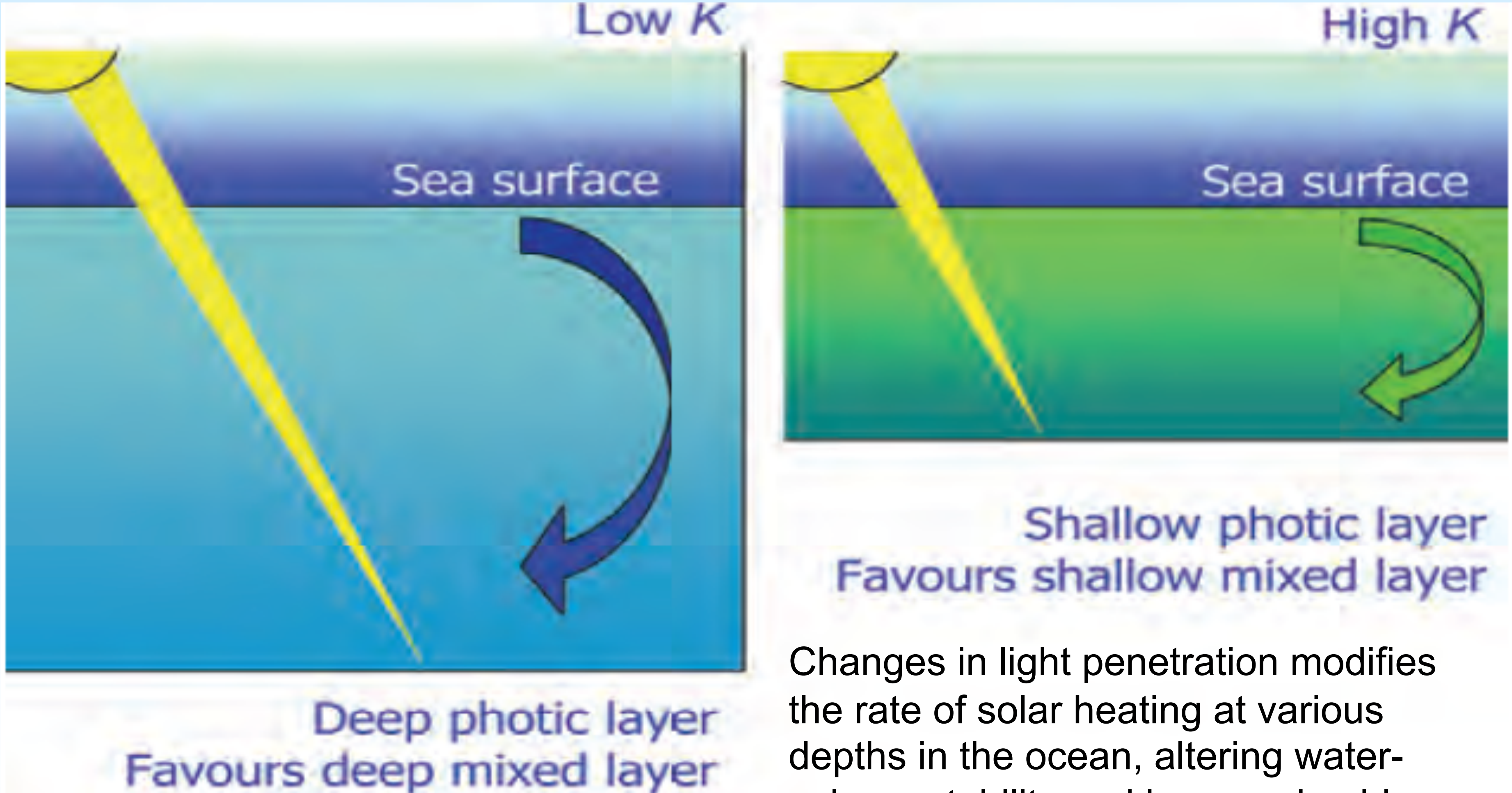


Illustration from IOCCG Report No.7

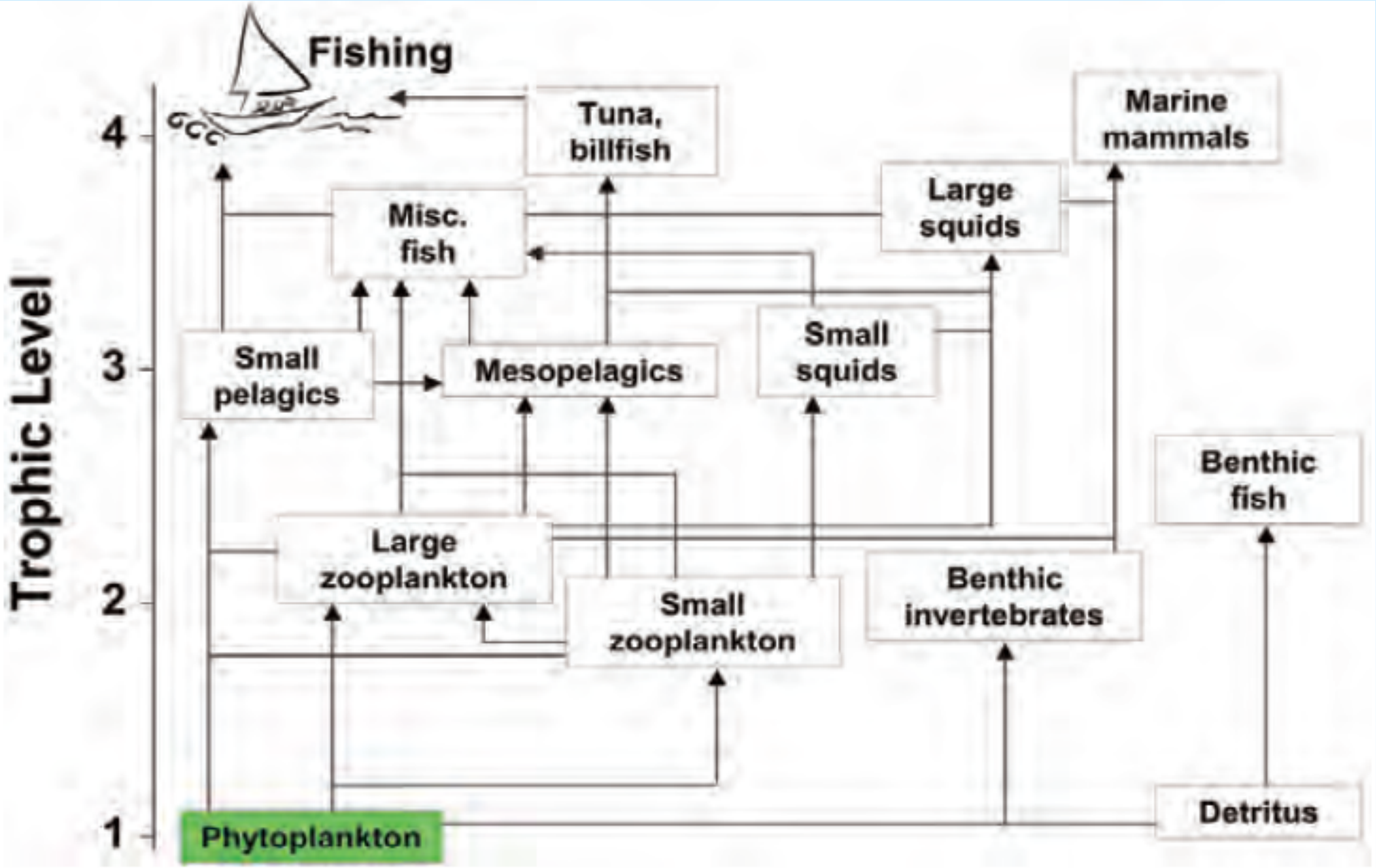
Changes in light penetration modifies the rate of solar heating at various depths in the ocean, altering water-column stability and hence mixed-layer dynamics.

•Ocean colour and fisheries

- Support for sustainable management of living resources
  - Understanding and monitoring conditions related to abundance and distribution of commercial fish species
  - Monitoring conditions related to the distribution, movement and migration of other animals - whales, dolphins, seals, penguins, sea turtles
  - Satellite data used in combination with numerical models of primary productivity, zoo plankton and higher tropic levels

Simplified oceanic food web

Linkages between phytoplankton and higher trophic levels



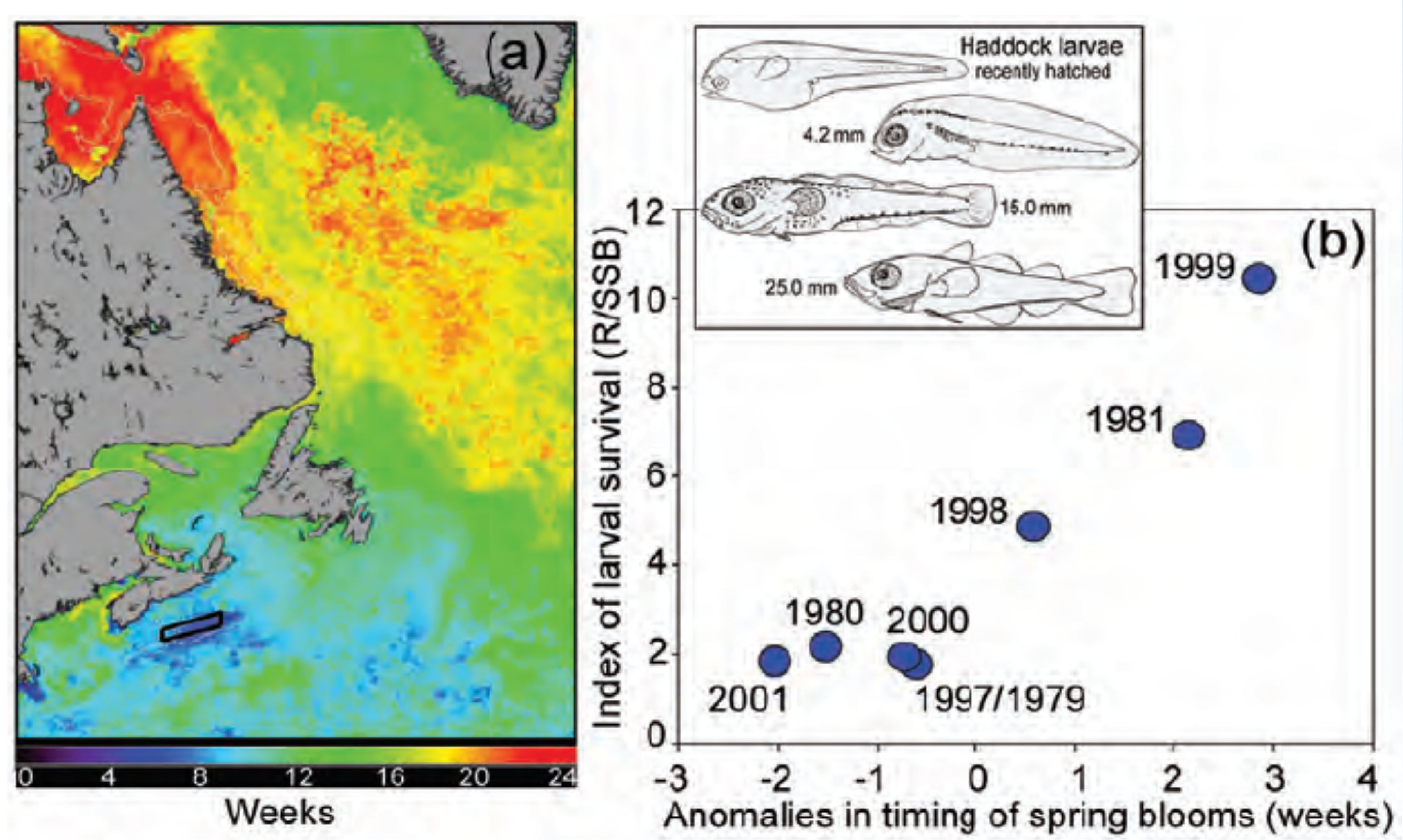
IOCCG Report 7, fig. 6.1. Modified from Pauly and Christensen (1995).

A key questions in fisheries science

- Understanding how environmental variability affects annual recruitment to different fish stocks
  - Larval stages of fish are strongly influenced by ocean circulation
  - Many larvae have narrow ranges of optimal thermal conditions
  - Available of a suitable food source depends on phytoplankton and zoo plankton abundance
    - Recruitment may be affected by the timing of seasonal blooms
- Satellite data from multiple sensors make it possible to study seasonal and interannual variability of key factors
  - Physical conditions (currents, temperature)
  - Food availability - studies using satellite data and numerical models

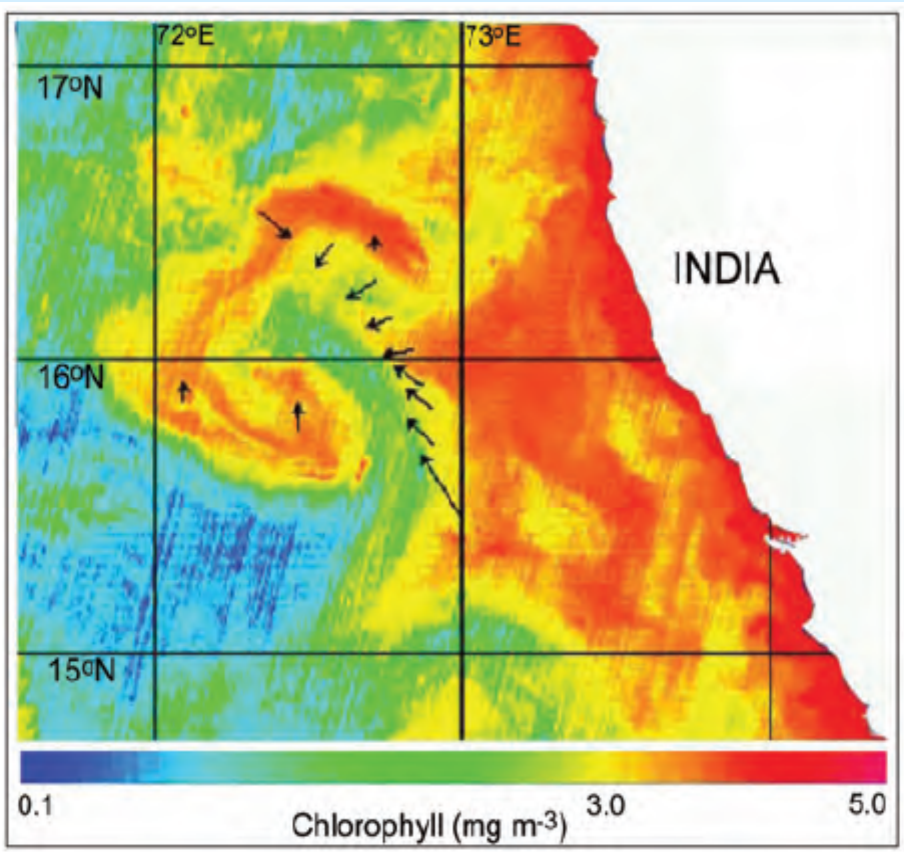
Timing of phytoplankton bloom and larval survival

Blue: early spring bloom (March); red: late spring bloom (July)



IOCCG Report 7, adapted from Platt *et al. (2003)*..

Harvesting



Chlorophyll map with areas of fishing activity indicated by arrows.

Source: IOCCG Report 7, map by Space Applications Centre, Indian Space Research Organisation.

- Ocean colour and SST maps used to guide fishing effort
  - Thermal or coulour gradients often indicate areas of high biological productivity
  - Temperature is also important in determining fish distribution
    - Different species have different preferred temperature ranges
  - Maps of potential fishing zones are provided to the fishing fleet
  - These need to be available in near realtime
- Maps also used by authorities to identify areas that need to be monitored for illegal fishing practices

Conservation of endangered species

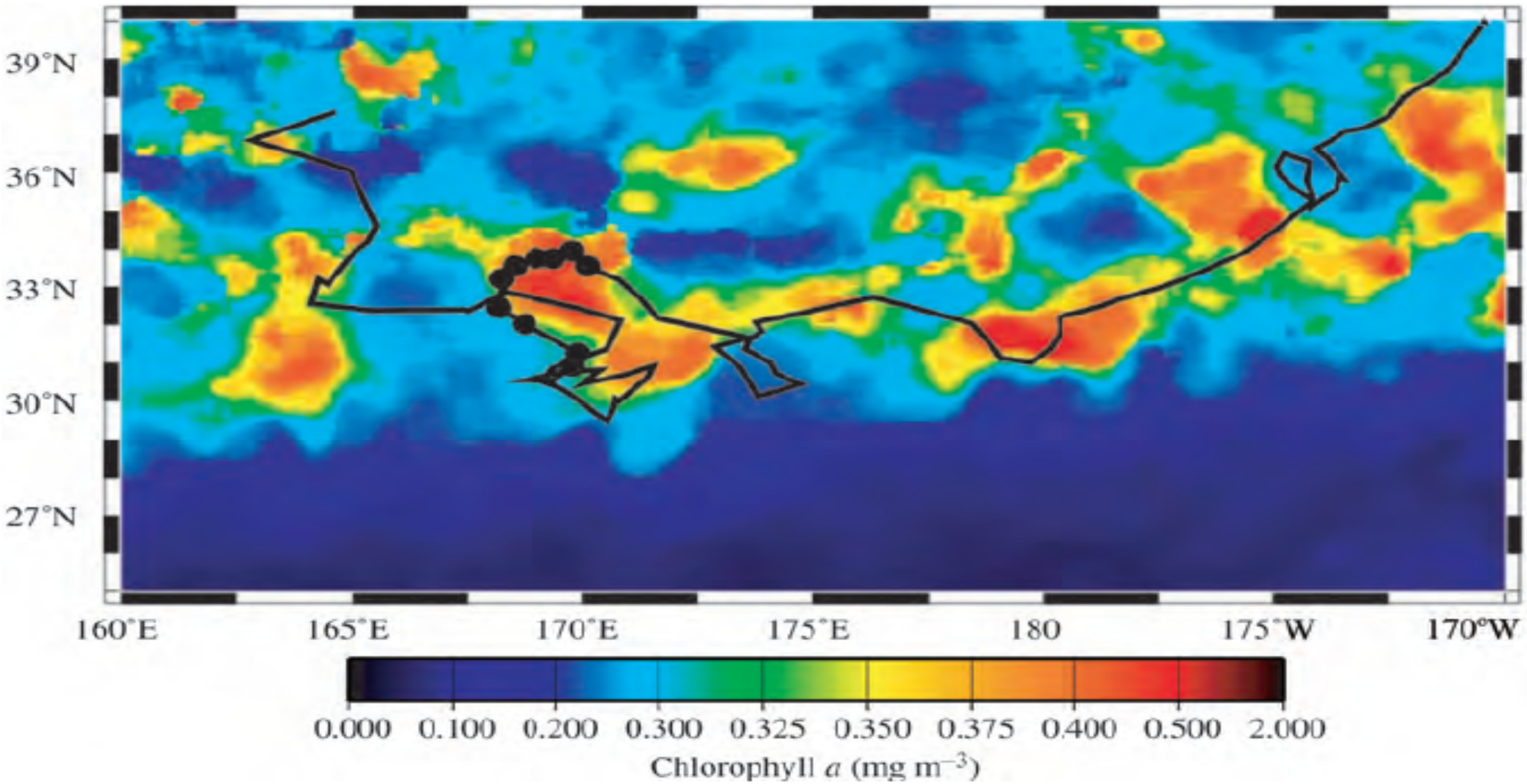


Figure 6.8 Track of a tagged Loggerhead turtle (black line) overlain on SeaWiFS chlorophyll data along the Transitional Zone Chlorophyll Front in the North Pacific Ocean. Figure adapted from Polovina *et al.* (2004).

IOCCG Report 7, Ch.6.

Water quality monitoring

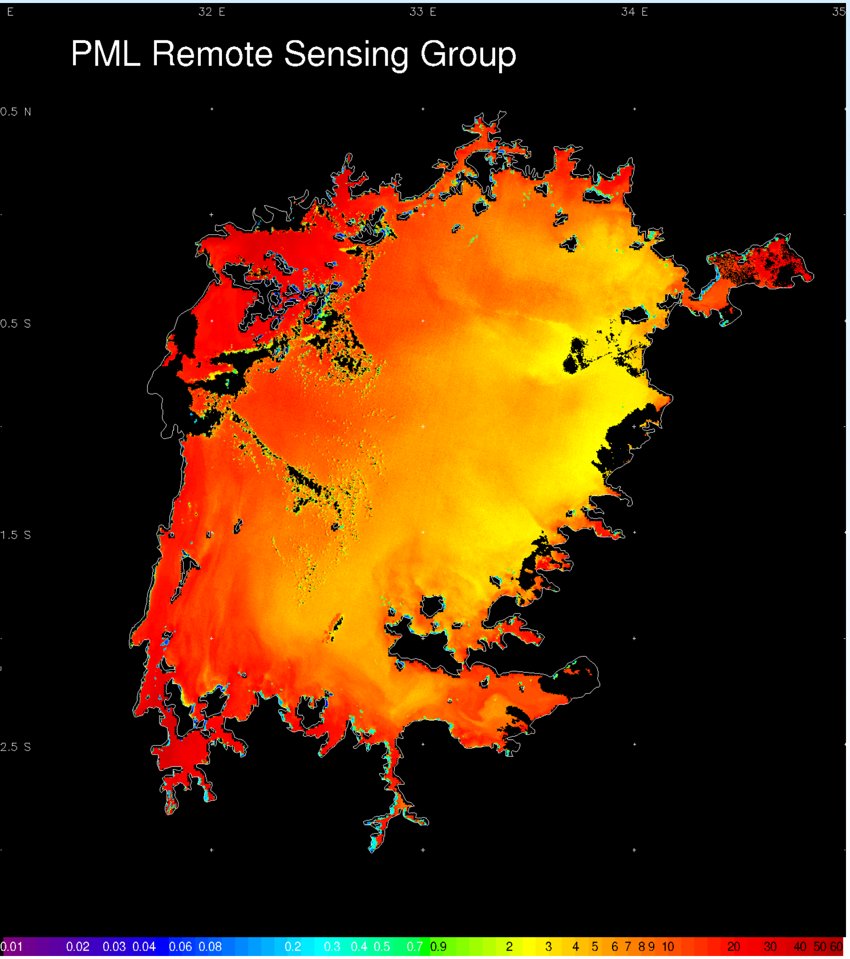
- Increasing pressure on water systems from climate change and human activities
  - Applies to coastal water, lakes, rivers, estuaries
  - Temperature changes, sea level rise, coastal erosion
  - Changes in rainfall and river run-off
  - Input of domestic, agricultural and industrial pollutants
- Assessments and monitoring of water quality needed to manage these pressures and ensure 'safe' waters
- Complex interaction of many factors
  - Satellite remote sensing: overview and regular, sustained observation – can provide early warning of problems
  - Need for in situ data, particularly factors not 'seen' by satellites
  - Numerical modelling to pull the complex factors together

Water quality indicators provided by satellites

- Water clarity / transparency
  - Commonly measured with a Secchi disk
  - Available from satellite data (Kd490)
    - Regional algorithms based on reflectances, tuned with in situ data
  - Reduction in water transparency can indicate problems
    - Eutrophication due to excess nutrient input (sewage, land run-off) increases phytoplankton production, and can create harmful blooms
  - Retrieval of absorption and backscattering from Rrs (λ)
- Coastal eutrophication (nutrient enrichment)
  - Caused by excess nutrient input (P and N) from sewage, agricultural land run-off, deposition of air pollutants in rain
  - Measured against a 'baseline' or reference condition
  - One of the most severe and widespread threats to estuaries and enclosed / semi-enclosed seas

Case-2 water products from ESA

EnviSat MERIS 2003 – 2012; [Sentinel 3 OLCI 2015 -]



MERIS chlorophyll data from Lake Victoria (ChloroGIN Lakes)

- algal_1
  - Global open ocean chlorophyll
  - Not suitable for lakes or sediment-laden coastal water
- Retrieved simultaneously:
- algal_2
  - Chlorophyll concentration
  - More suitable for lakes/coasts
- TSM = Total Suspended Matter
- Yellow_ subs
  - Coloured dissolved organic matter absorption coefficient

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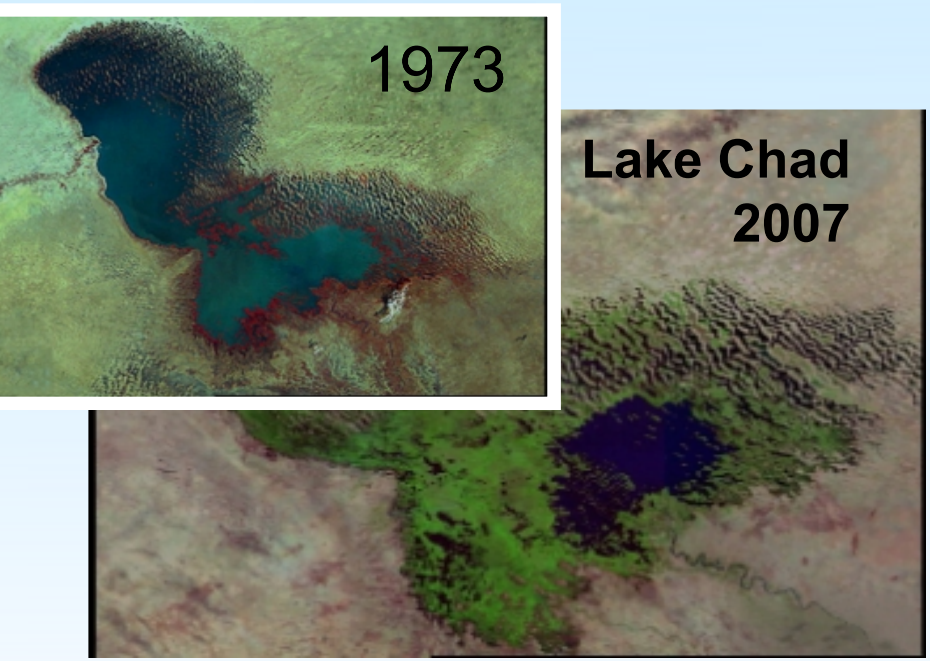
Other parameters of interest for inland waters



- Lake Surface Water Temp.
  - LSWT from thermal IR data
  - Control on productivity
- Lake level / extent
  - Extent from optical or SAR data
  - Level (height) from altimetry
  - Changes in level / extent due to droughts and floods
- Floating or submerged macro-algae or higher plants
  - Contribute to reflectance
  - Ecological importance
  - Can indicate eutrophication

Harmful algal blooms

Aerial photograph of an extensive bloom of the dinoflagellate *Gonyaulax polygramma in False Bay, South Africa on 23 February 2007 (from* Pitcher *et al., 2008).*

- Often associated with release of biotoxins by certain species present in the bloom
- Even if not toxic, intense blooms can cause problems for fish and other marine life, by clogging gills
- Breakdown of dead algae can deplete the water of oxygen causing anoxic conditions near the bottom
- Ocean colour offers synoptic, frequently acquired data used to monitor blooms

Monitoring a high biomass HAB in the southern Benguela

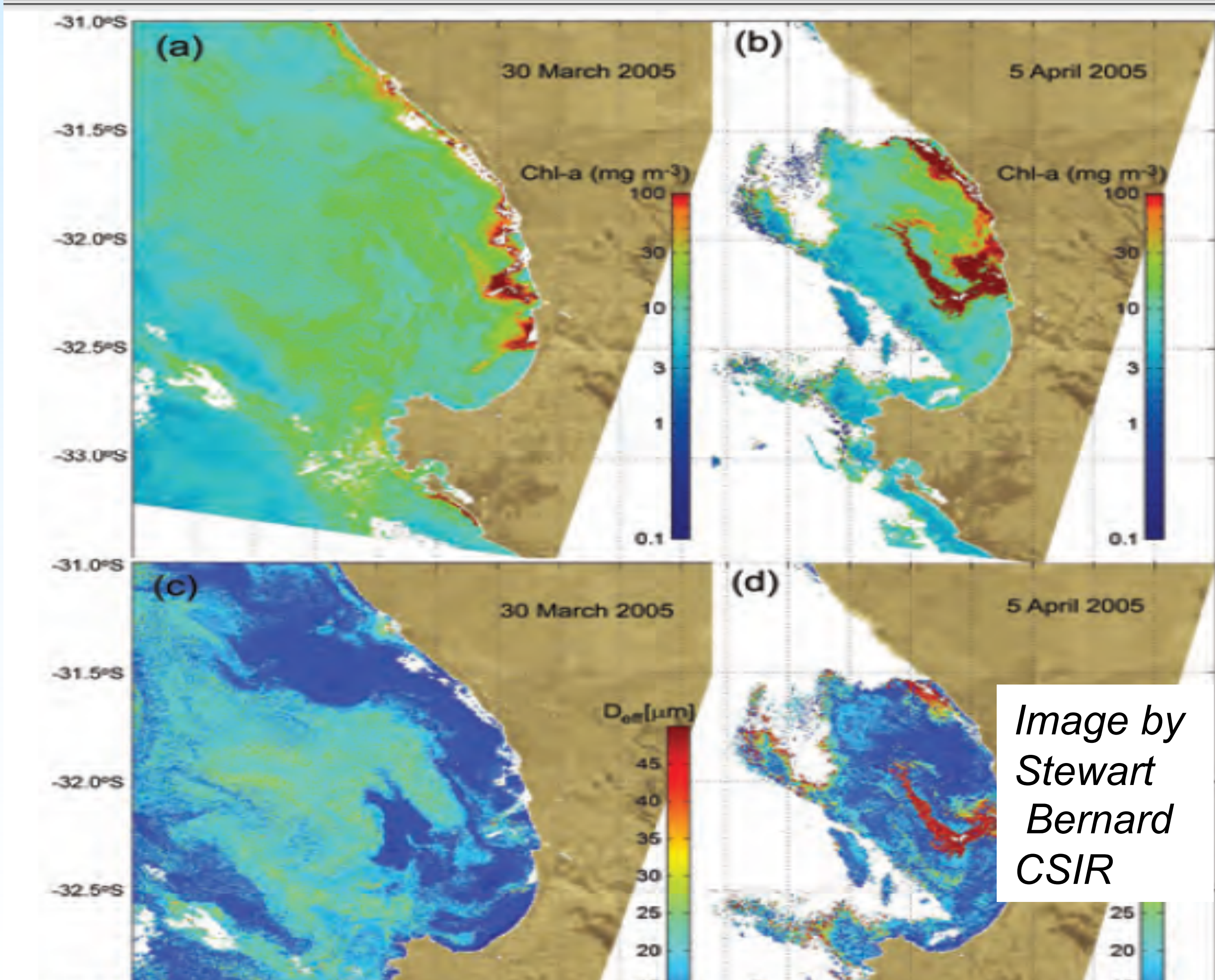


Image by Stewart Bernard CSIR

Transport of sediment and pollutants

Satellite view of the Bangladesh coastline showing discharge of sediments from the Ganges River. Image acquired by the European Space Agency, ESA's MERIS sensor 8 Nov.2003.

Suspended sediment

- Ocean colour is used in detection and quantification of marine (aquatic) suspended sediments
  - Can also provide shallow water observations of changes in bottom topography caused by sediment transport
- Causes of increased suspended sediment concentrations
  - Dredging operations
  - Natural processes such as storm and tides
    - Wind, waves, bottom currents
  - Increased land run-off, e.g. after storms
    - Soil erosion
- Damage to benthic habitats when sediments settle
  - Sea grass beds and similar vegetation
    - nursery grounds for larval fish
  - Coral reefs

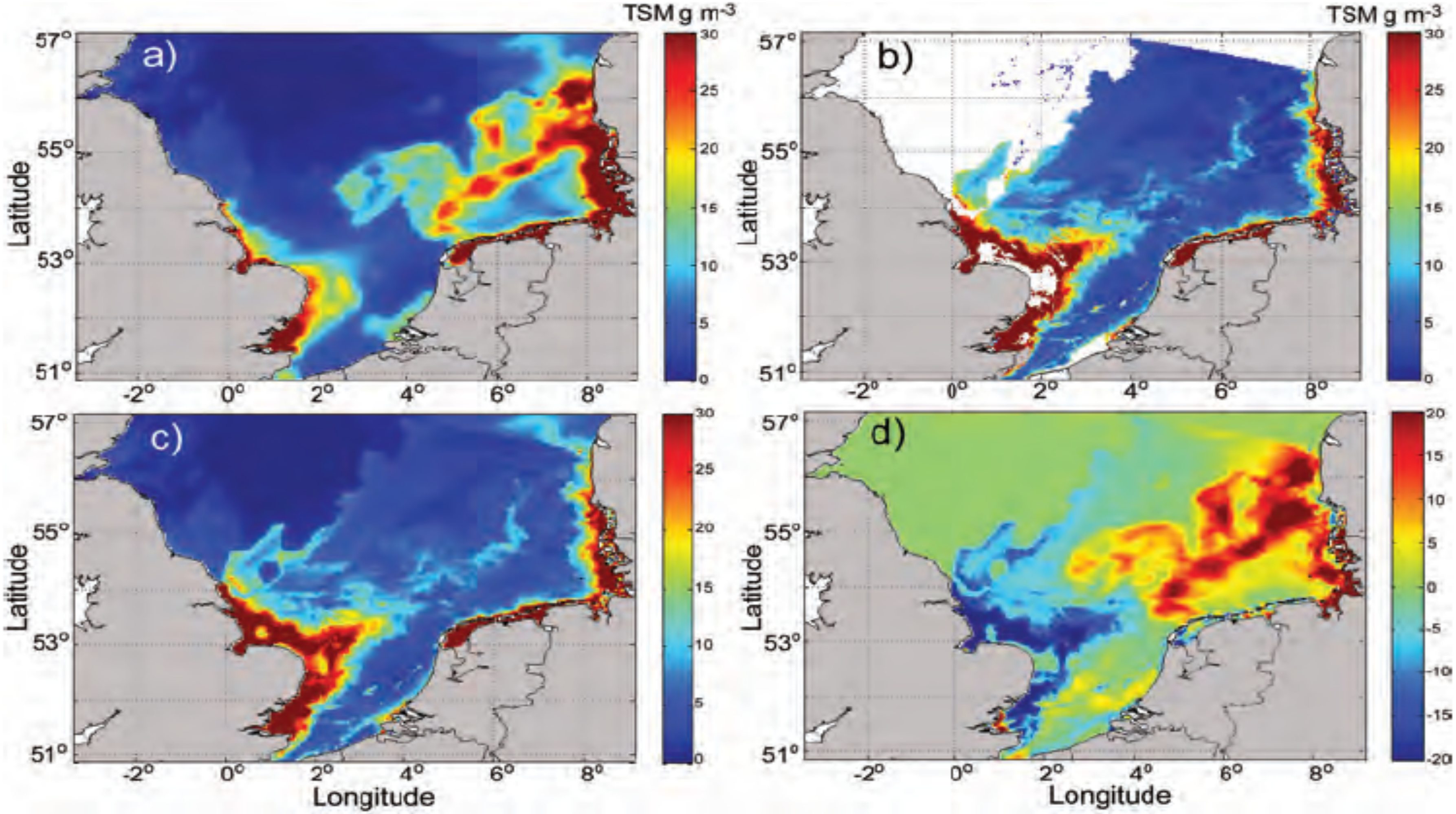


Figure 7.8 An example of data assimilation using the optimum interpolation method: a) surface concentration as calculated with the SPM transport model; b) surface sediment concentration derived from MERIS on 22 March 2003; c) model result after assimilating the MERIS data and d) difference between model results before and after data assimilation. (Credit: Image provided by Gerhard Gayer and Mikhail Dobrynin (GKSS, Germany), MERIS data provided by the European Space Agency).

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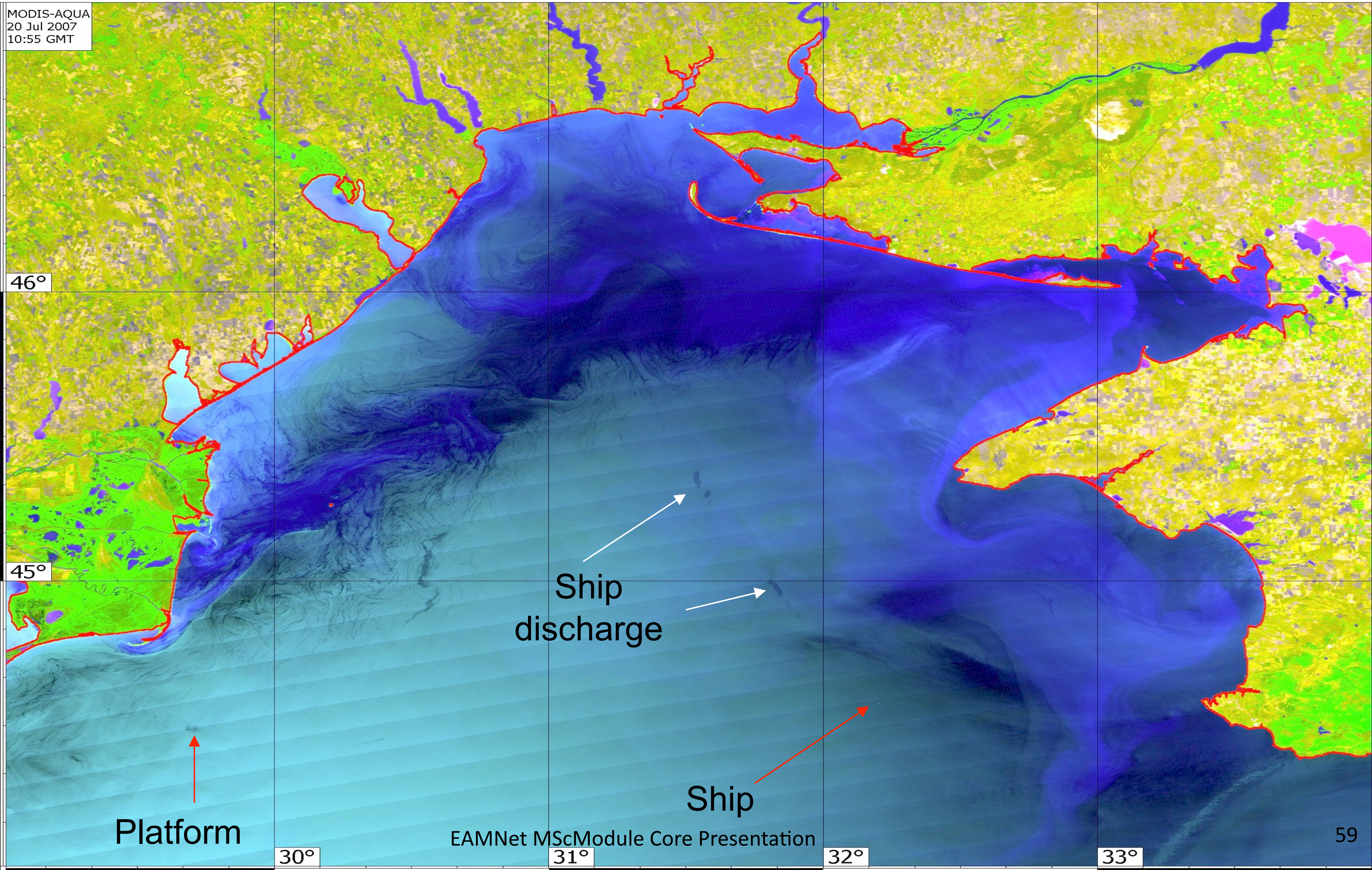
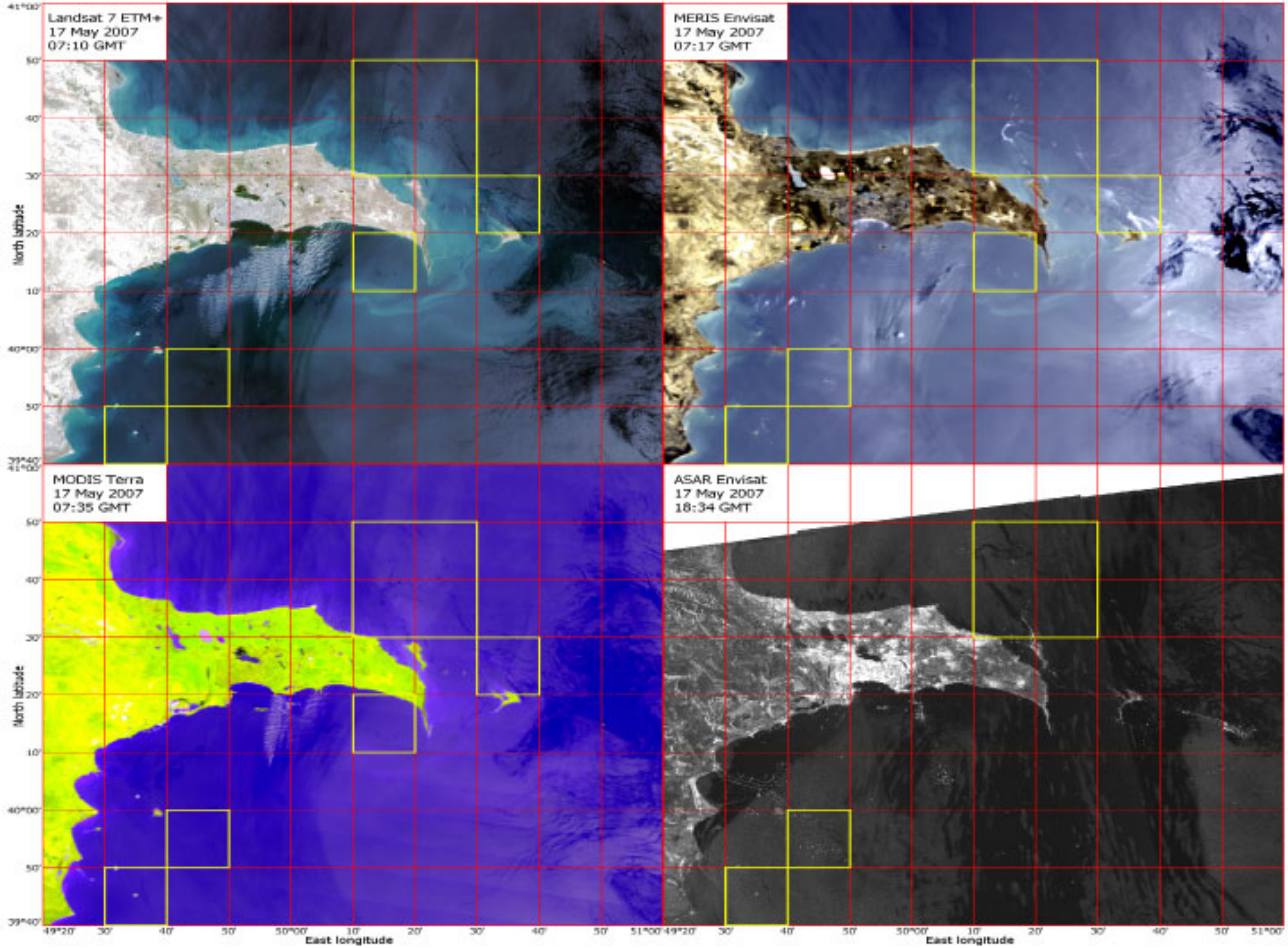
Oil spill monitoring (1)
Monitoring of off-shore operations and shipping





Landsat 7 ETM+
17 May 2007
07:10 GMT
MERIS Envisat
17 May 2007
07:17 GMT
MODIS Terra
17 May 2007
07:35 GMT
ASAR Envisat
17 May 2007
18:34 GMT
41°00'
50'
40'
30'
20'
10'
40°00'
50'
39°40'
North latitude
49°20'
30'
40'
50'
50°00'
10'
20'
30'
40'
50'
51°00'
East longitude

Oil spill monitoring (2)
Using RS to plan and direct oil spill response

Dispersant spraying

Containment with booms

Controlled burning

Skimmer

- Satellites: daily strategic overviews
  - ❖ SAR / optical sensors map the spill
    - Wide range of other sensors give data to aid interpretation of SAR / optical images
    - Synergy of sensors from many satellites => more reliable and frequent information
  - ❖ Data for input into oil spill models
    - Wind, waves, currents (altimetry, scatterometry, SST, ocean colour)
    - Oil location / movement from SAR / optical => evaluate predictions
- Aircraft: short-term tactical info.
  - ❖ UV, Visible/NIR, thermal IR, radar, lidar,
  - ❖ Used to direct clean-up operations

22 April 2010: the Deepwater Horizon oil rig in the Gulf of Mexico sinks in 1,500m of water after an explosion and fire on 20 April. The accident led to a large oil spill from the well nearly a mile below the ocean surface.

Photo: U.S. Coast Guard

Background: NASA MODIS-Terra quasi true colour composite image of smoke from the burning rig on 21 April 2010. **Inset:** Band 7-2-1 shows the fire (red dot).

MODIS-Aqua overview 25/4
250m resolution

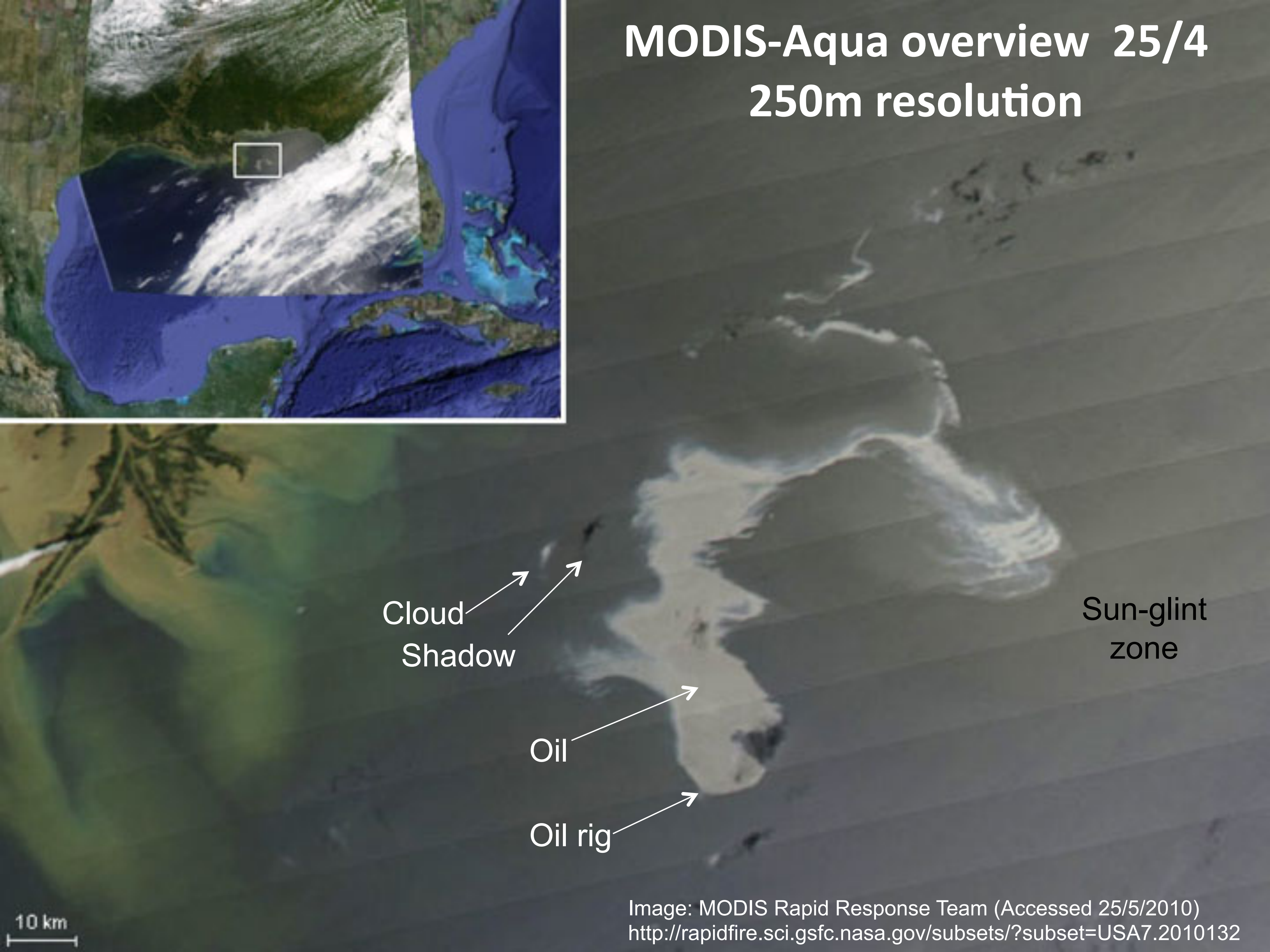
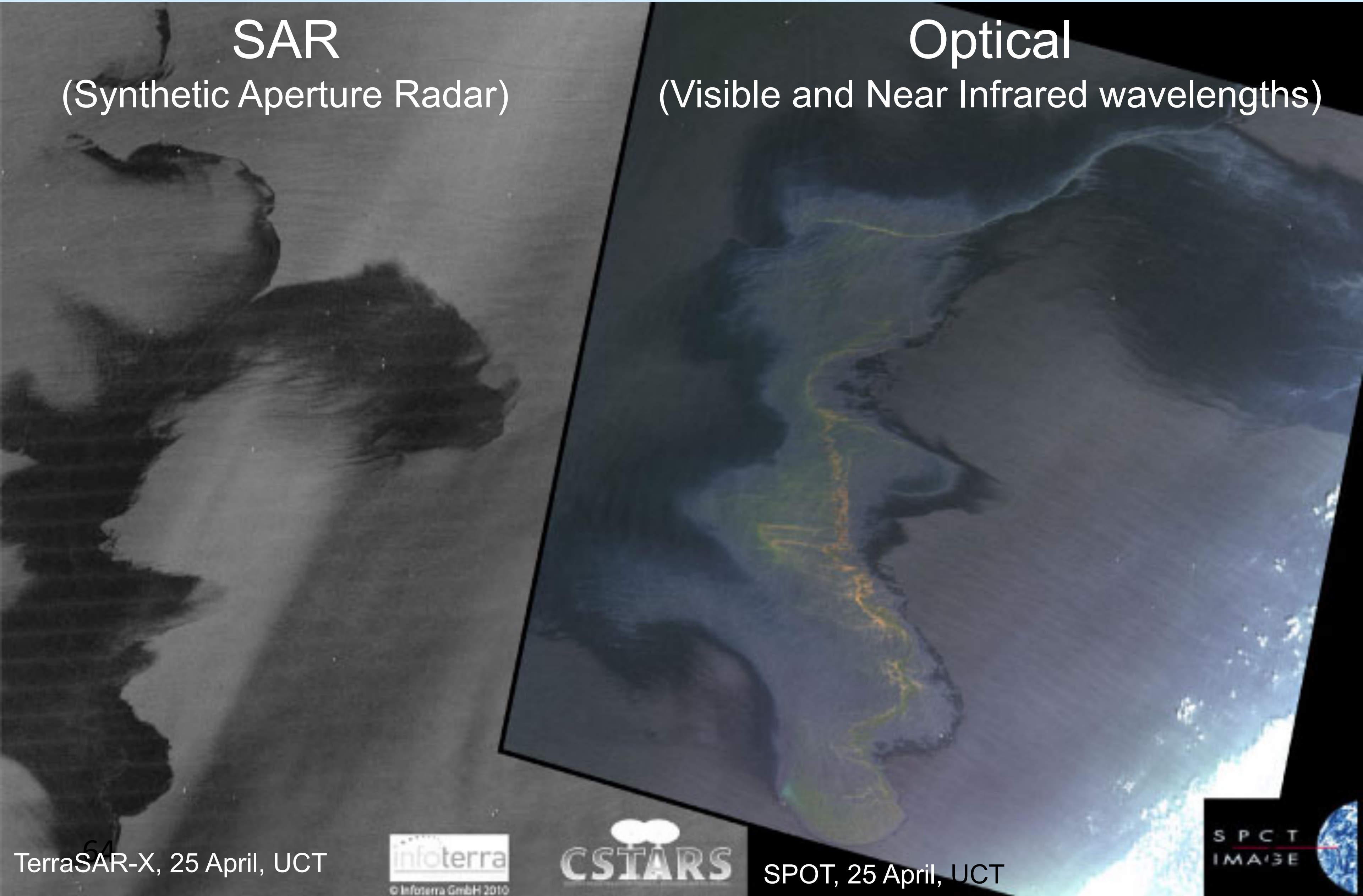


Image: MODIS Rapid Response Team (Accessed 25/5/2010)
http://rapidfire.sci.gsfc.nasa.gov/subsets/?subset=USA7.2010132

Main sensors for oil spill detection from space



Ocean colour monitoring of oil spills

- Uses TOA radiances
  - Standard atmospheric correction removes the signal
- Surface oil is detected based on contrast between the oil slick and surrounding water
  - In the sun-glint zone oil appears brighter than the water
    - Oil has a higher refractive index than water, so reflects more light at the surface
  - Towards the edge of the glint zone contrast reverses and become negative
    - Oil dampens capillary (cm wavelength) waves, so there is less sunglint directed towards the sensor (similar mechanism to SAR)
  - Outside the glint zone oil is darker, but very thick surface oil is often brighter in the red and NIR
- Disadvantage: clouds prevent measurement
- Best used in synergy with SAR

Commercial shipping and port operations

- Movement of sediments can alter the course or reduce the depth of shipping channels
  - Sediment is mobilised by
    - Dredging
    - By wind, waves and bottom currents
- Data from optical sensors used to monitor the movement of sediments in ports and river estuaries
  - Spectral reflectances
    - Suspended particulates increase backscattering & reflectance
    - Wavelength range 550 – NIR particularly useful
  - MERIS TSM data – standard case 2 product
  - Higher resolution 'land' sensors can also be used if they have a blue channel

Shallow water bottom topography

- Calculation of water depth (z) from RS data requires
  - ❖ Water column properties
    - Spectral reflectances, Rrs(λ) and diffuse attenuation coefficient, Kd
    - Derived from an adjacent deep water area and assuming that they do not change between deep and shallow areas (!!!)
      - – Avoid satellite images following storms or floods
  - ❖ Estimates of bottom albedo (A)
    - Obtained from *in-situ* ground data and by regression analysis of Rrs (λ)
  - ❖ Most effective when A, Rrs (l), Kd and z are retrieved together
- Ground truthing with *in-situ* data
  - ❖ comparison with bathymetric charts where available
  - ❖ Depth measurements at a few locations
  - ❖ In situ observations of bottom albedo / habitat types
- Most effective in clear water (low Kd490)
- Spatial resolution required: 30 m or better

Military applications

- Water clarity is a concern for mine detection/neutralization
  - Clear water makes it possible to detect objects, and changes in objects on the sea floor, along beaches and in ports
  - Turbid water causes problems for operations by divers tasked with mine detection, and for planning of operations to neutralize mines successfully and safely.
- Satellite ocean colour was used to provide water clarity information in several military operations
  - During hostilities in the Middle East
  - Before intervention in the Sierra Leone civil war in 2000
- Optical analysis of water column and bottom characteristics is used in port protection and for water clarity predictions.

Spatial scales for different applications

Applications/Issues	Spatial Resolution x Extent	Temporal Resolution	Examples of suitable platforms/sensors
River plumes outfalls	(30 m – 1 km) x (300 m – 100 km)	Hours – weeks	GLI, MERIS, MODIS, NEMO, SeaWiFS
Tidal plumes, jets, frontal dynamics	(100 m – 1 km) x (1 km – 10 km)	Hours	Airborne, SEI
HAB, aquaculture, coastal water quality	(100 m – 1 km) x (1 km – 100 km)	Days – weeks	GLI, MERIS, MODIS, NEMO, SeaWiFS
Bathymetry and shallow benthic habitat: distribution, status	(1 m – 30 m) x (1 km – 100 km)	Weeks – months	Airborne platforms, ARIES, NEMO
Maritime operations: navigation, visibility	(30 m – 1 km) x (30 km – 100 km)	Hours – days	MERIS, MODIS, NEMO, SeaWiFS
Oil spills	(100 m – 1 km) x (1 km – 100 km)	Hours – days	Airborne, MERIS, MODIS, NEMO, SEI
Operational fisheries oceanography	1 km x 1000 km	Days	GLI, MERIS, MODIS, SeaWiFS
Integrated regional management	(30 m – 300 m) x (30 km – 300 km)	Days	MERIS, NEMO

Source: IOCCG Report No. 3